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Photodiode Array Position Sensing of a Model in a Magnetic Suspension Wind Tunnel

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Photodiode Array Position Sensing of a Model in a Magnetic Suspension Wind Tunnel

by

R. H. Moore

A report submitted for B.Sc. Electronic Engineering

May 1981

Supervisor: Dr. A.P.Dorey

SUMMARY

This report investigates the use of a 512 element linear photodiode array to determine the position of a model in a magnetic suspension wind tunnel.

A suitable optical system is developed and a circuit is designed to give a digital and analogue output of position. This is incorporated into the heave control loop of an existing magnetic suspension wind tunnel and is shown to operate satisfactorily. Investigations are carried out into the immunity of the array output to smoke inserted in the wind tunnel and a number of recommendations are made for further work.

CONTENTS

CONTENTS (cont.)

1. INTRODUCTION

This project investigates the use of a self scanned linear photodiode array to determine the position of a model in a magnetic suspension wind tunnel. This tunnel suspends the model without any requirements for struts to hold it stable thus enabling realistic observations of windflow around the model. However an accurate method is needed to determine the position of the model in order to control the magnetic field exerted on it.

At present the only method used to detect the position is to cause the model to intercept a light beam. The amount of light then passing determines the position of the model and is detected by a photosensor whose output is used to control the magnetic field strength - see figure 1.

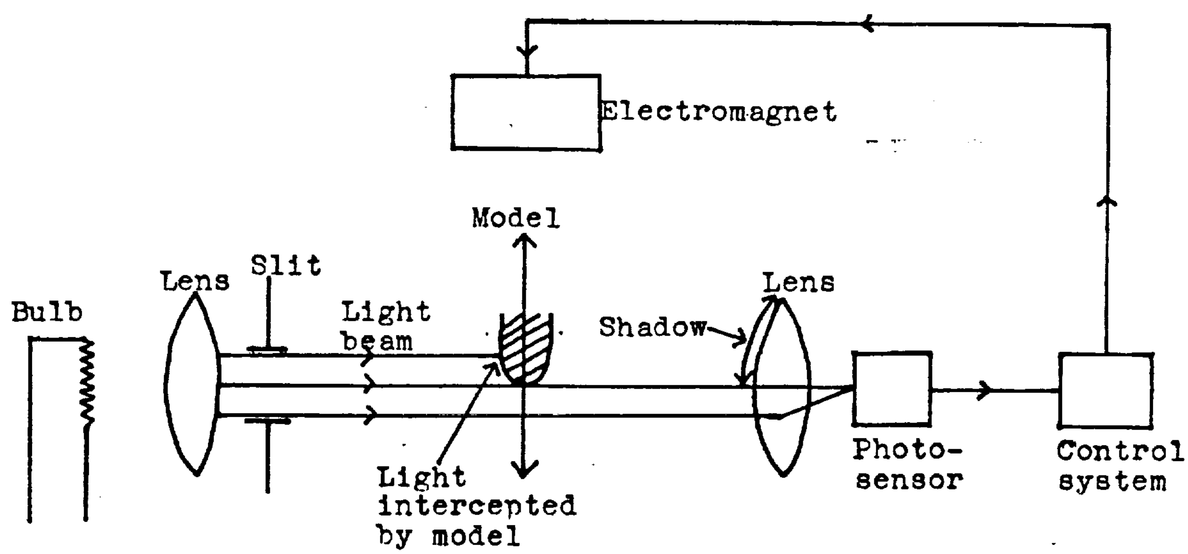


Figure 1. Light Beam Position Sensing

There are three advantages of using a photodiode array:

(i) To overcome problems of photosensor system when smoke is inserted into the tunnel to investigate

[illegible]

(ii) A future large wind tunnel using magnetic suspension will require alternative backup systems for detecting the position of models, in case any one of them should fail to work.

(iii) Specially shaped models will not be required since one may be able to use an optical reflective target system on the model - see appendix 1.

Two photosensors are mounted in a horizontal plane about 15 cm apart and these control both heave and pitch motions. Only one sensor is required to control heave motion and the photodiode array was mounted in between the two photosensors. This was switched into the heave control loop and used the existing control system for the photosensors. An analogue voltage signal (0 to 5 volts) was required depending on the position of the edge of the shadow up and down the array. A driver board providing scanning logic and signal processing for the photodiode array was bought from Integrated Photomatrix Ltd. Additional circuits were built which counted how many of the array diodes were illuminated and converted this number to the required analogue signal.

2. SELF SCANNED PHOTODIODE ARRAYS

This section provides background information on self scanned photodiode arrays and some detailed information on the Integrated Photomatrix Ltd. system used in the project.

2.1 DEVELOPMENT OF PHOTODIODE ARRAYS

The possibility of forming image sensors from arrays of silicon photodiodes on a single silicon chip had been recognized since the inception of Integrated Circuit technology some twenty years ago. Two problems immediately faced the designers:

Firstly, the array size was limited not by the number of diodes that could be incorporated on the silicon, but by the number of output leads necessary to form connections to these diodes. To circumvent this problem, it was necessary to scan the diodes and thus to multiplex them into a single output lead by means of switching circuitry on the same chip.[1]

The second problem was that of detecting the minute photocurrents produced by the very small diodes. This was overcome by using the method of charge integration[1] [2] - see section 2.2.

Early development was spurred by one main advantage as seen then over electron image scanning tubes such as the vidicon. This was the diodes lack of retention of previous images, which enabled completely new information to be read out at each scan of the array. However a further unique property of such arrays was only realized later - that of the high positional accuracy (better than 10^{-6}m.) of each diode which made optical gauging systems, and position sensing systems such as developed in this project possible.

Serially multiplexed arrays up to 2048 photodiodes and over 25mm have now been built with scan rates up to 10 MHz. Meanwhile 2 dimensional arrays of 256 by 256 diodes have become possible. These are used for area gauging, character recognition, guidance systems, and in the future for television imaging.[2][3]

2.2 SCANNING METHOD AND CHARGE INTEGRATION

The photodiode array to be used incorporates MOS transistor switches which access each diode individually and connect it to a common video output line. The switches are turned on and off in sequence by two internal shift registers, each register accessing alternate diodes. These registers are physically placed along with their associated MOS switches on the two opposite sides of the array since this arrangement enables the closest possible stacking of the diodes to be achieved. Two non-overlapping clock pulse trains drive the registers.[3][4]

The photodiodes operate in a reverse bias light integrating mode. Across each photodiode there is a parallel storage capacitor. The initial scan-pulse propagating through the shift register cause each photodiode capacitor in turn to be charged to some negative voltage of a few volts thus reverse biasing the photodiode. Under dark conditions this charge will be held sensibly constant for a period of the order of 1ms.[1]. However if light is present, the capacitor will lose charge through the photodiode. When the next scan pulse reaches the photodiode, the capacitor is recharged to its original level. The charge pulse required to do this, is of course, equal to the total charge lost, and becomes the video output signal. It is also the photocurrent integrated over the whole period so this time between successive scan pulses is known as the integration time or scan time.

See appendix 2 for a simplified circuit diagram of the array.

2.3 THE 'INTEGRATED PHOTOMATRIX' ARRAY SYSTEM

For this project a 512 element array produced by Integrated Photomatrix Ltd. was used, along with their own processor and driver boards.

The complete system consists of three boards: an array board, a driver board and a processor board. Figure 3 shows a block diagram of the system. The array board consists of a socket for the array, clock drivers and a pre-amplifier. The driver board contains a master clock oscillator and logic to generate the clock and scan pulses for the array and synchronised pulses for the signal processor. The processor board produces a 10 volt maximum boxcar video output from an integrator and sample and hold circuits. Figure 2 shows a typical video output from the board system with the array half covered.

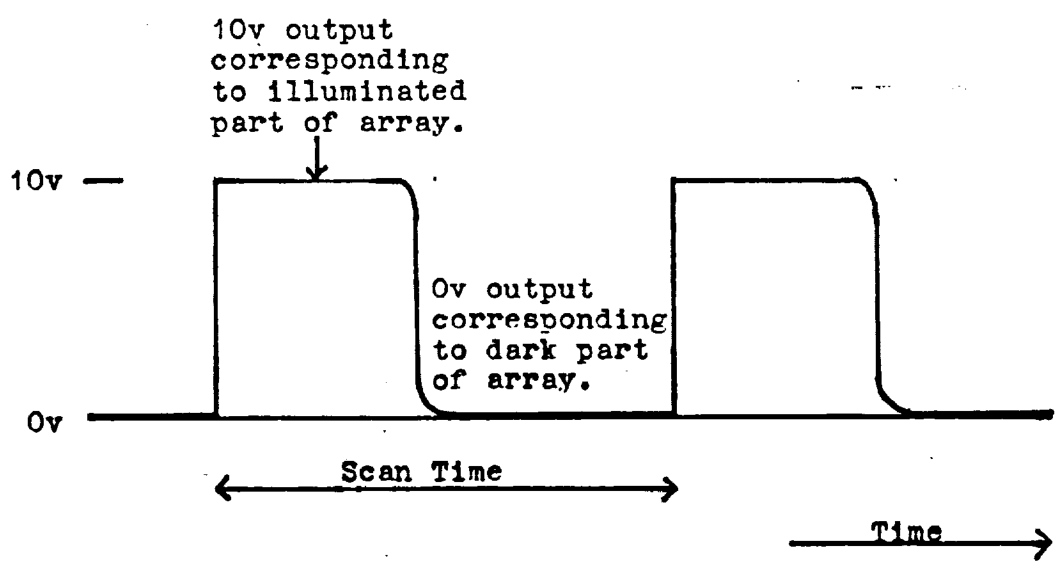


Figure 2. Typical Video Output for Array Half Covered

A number of signals are available from the boards. The following are used : the video output signal, scan start A and B pulses and the oscillator output[5].

The photodiodes have a pitch of 0.001 inches (=0.025mm) and thus the total array length is 0.512 inches (=13mm). The array width is 0.005 inches. Each photodiode has a light sensitive surface covering 90% of its length. More detailed performance figures are quoted in the information sheet in appendix 2.

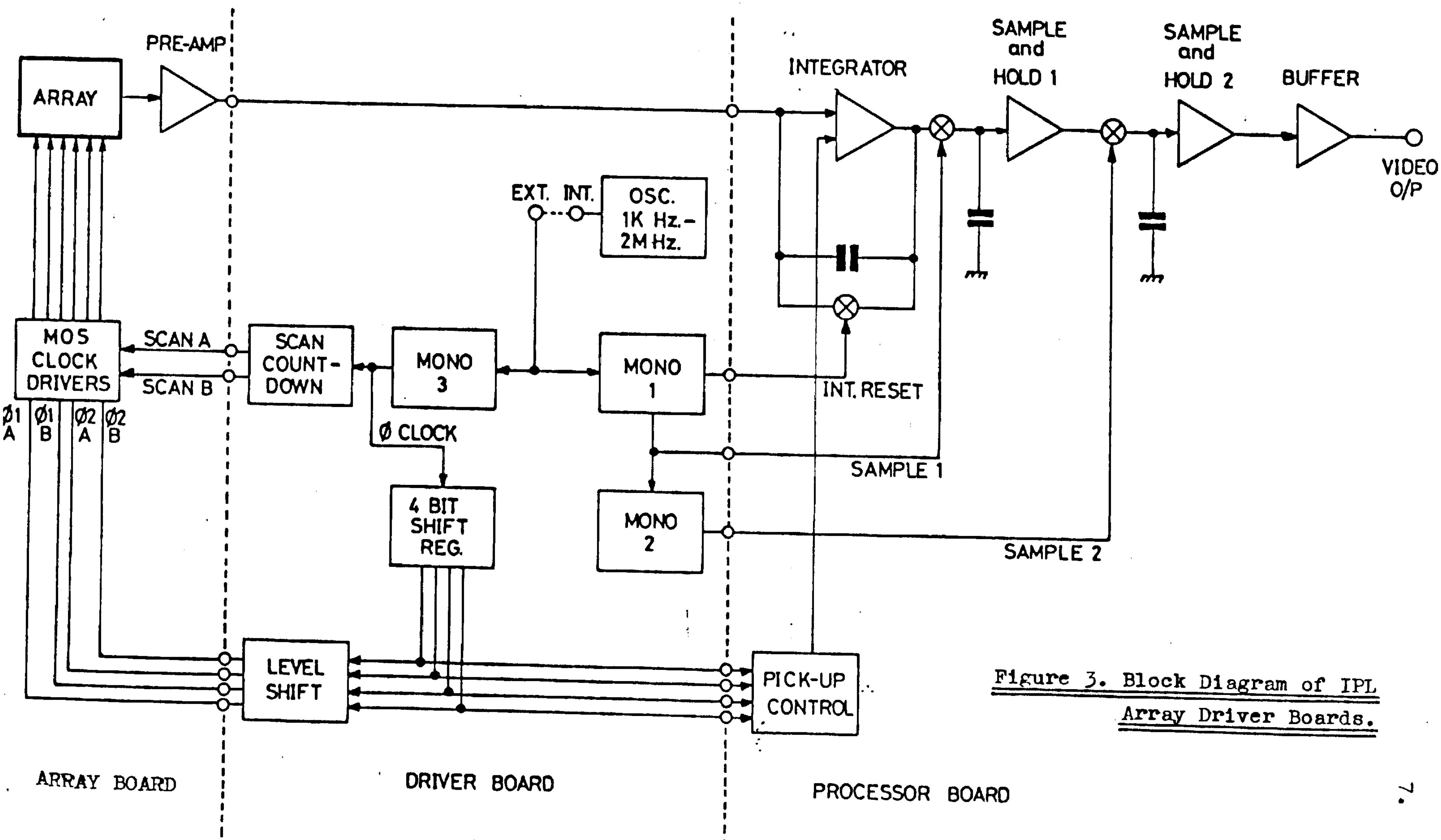


Figure 3. Block Diagram of IPL Array Driver Boards.

3. ILLUMINATION OF THE ARRAY

The method of illuminating the array is very important and is considered in this section.

3.1 EXISTING SYSTEM FOR PHOTOSENSORS

The illumination system used in the wind tunnel for the photosensors is shown in figure 4.

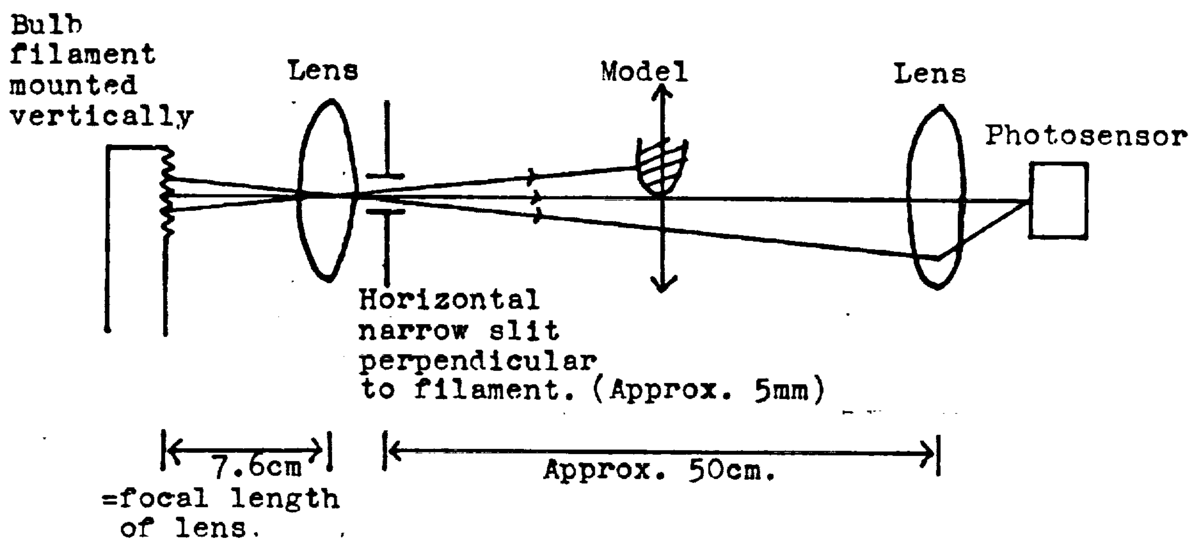


Figure 4. Illumination System for Photosensors

As the model moves down, it intercepts more light. Therefore the photosensor gives a lower output and the position of the model can be determined by this current. The 10 watt bulb has a very fine, closely wound filament. A lens is mounted at its focal length from the filament thus giving as closely as possible the effect of a parallel beam of light output. This beam is shone through a narrow slit which is perpendicular to the filament to effectively give a point source of light. This arrangement gives a very sharp image and uniform light intensity across the beam.

3.2 LIGHT SOURCE FOR ARRAY

It would have been convenient to use one of the existing light sources for the photodiode array in the wind tunnel but it was discovered that the 10 watt bulbs were not bright enough to use for this purpose. Therefore a different bulb was required which must be run from a d.c. source. A 55 watt, 12 volt halogen car headlamp bulb was selected for use. The aim was to get the transition between light and dark on the array window to be as sharp as possible to give the squarest video output from the driver board, and to obtain uniform light intensity across the beam. Four factors affect the operation and will be discussed in turn:

(i) Intensity of source.
(ii) Background lighting.
(iii) Focusing of image.
(iv) Wavelength of light source.

3.2.1 Intensity of Source

The illuminated video level output from the IPL board can be adjusted with a preset from 1 volt to 10 volts. However a certain minimum intensity of light is required before the output reaches the level set by the preset - this intensity being the same regardless as to where the preset is adjusted to. Figure 5 shows three video output waveforms for differing light intensity. In all of them the preset is adjusted to give maximum (10 volt) illuminated output and the chip is covered at a point approximately two thirds of the way across using the lighting arrangement shown in figure 4, (with headlamp bulb, and photodiode array placed where second lens is).

The first waveform shows the video output when the intensity of the source is turned down to give a 5 volt illuminated output. The second shows the video output when the source has just been turned up enough to give a 10 volt illuminated output, and the third waveform when the source

Plot 1. Light intensity adjusted to give 5v illuminated output.

Plot 2. Light intensity adjusted to give just 10v illuminated output.

Plot 3. Light intensity turned up to give much more light than required for 10v illuminated output.

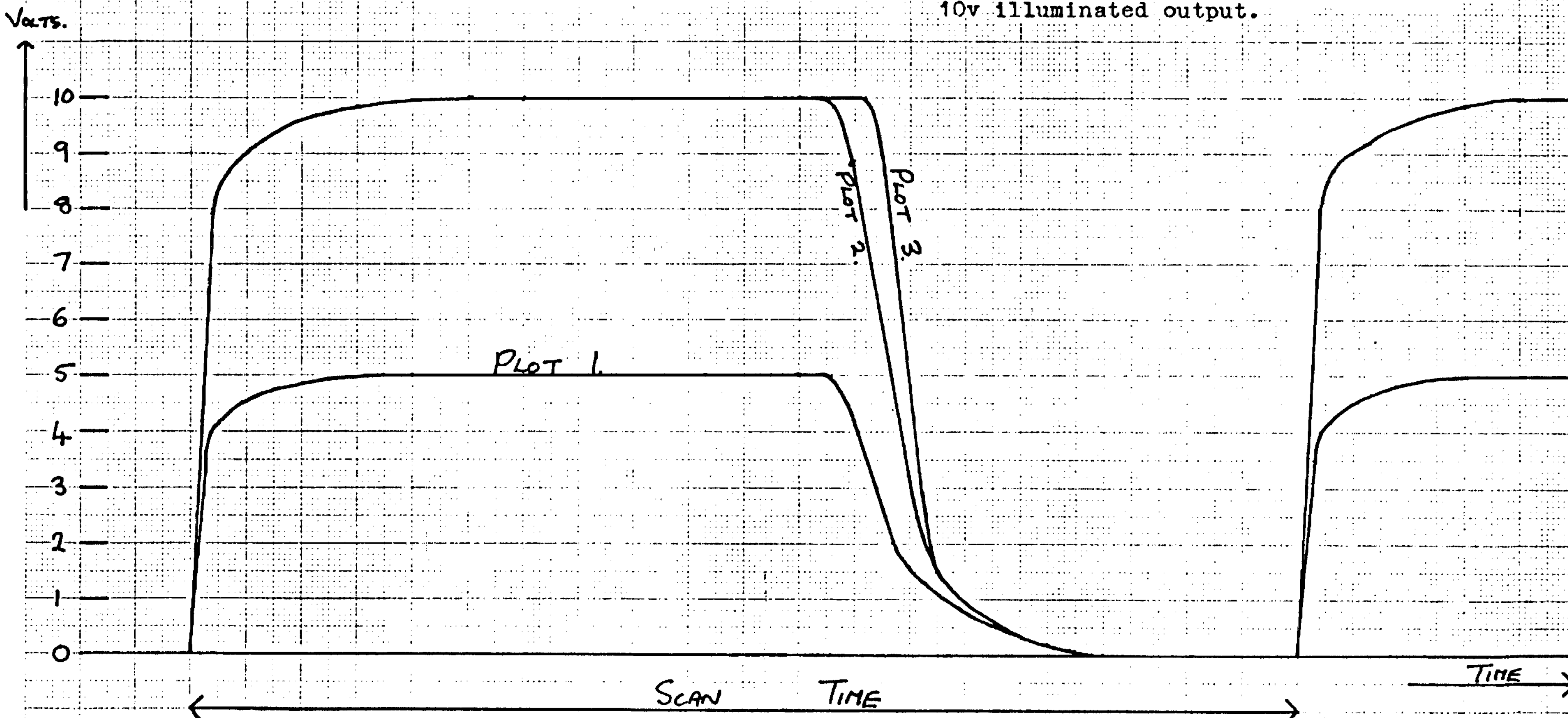


Figure 5. Video Output Waveforms for Different Light Intensities.

has been turned to its maximum intensity to give more light than is required for 10 volts.

An arbitrary voltage (threshold level) is taken on the falling edge as being the decision point to determine the position of the model. The slope of this edge must therefore be considered carefully as the model will appear to be at slightly different positions for different threshold levels up and down the slope.

From the three waveforms it can be seen that the first two take the <u>same</u> time to change from zero volts to their maximum level. In other words, the second waveform with a 10 volt maximum has a sharper edge than the 5 volt waveform. This is to be expected as this edge is a geometric function of the penumbra (transition from light to dark) only. However the slope of the final waveform in this diagram is even sharper. The array is being 'overloaded' by the intense source and some of the photodiodes in the penumbra are giving a maximum ten volt output; see figure 6. Thus the slope is sharpened up.

Three points emerge from this discussion which all show that the maximum intensity light source possible should be used:

(i) In order to work with different threshold voltages for deciding on the point where the video output goes from light to dark it is evident that the sharpest edge possible is required so that the position across the scan changes the least possible amount when the threshold voltage is changed. See figure 7.

(ii) As explained in the introduction, one of the objectives of this project is that one should be able to introduce smoke into the tunnel without changing the sensed position of the model. The effect of smoke will be to reduce the intensity of the light source and this will reduce the slope of the transition edge and eventually bring the illuminated level output below the threshold level. It is

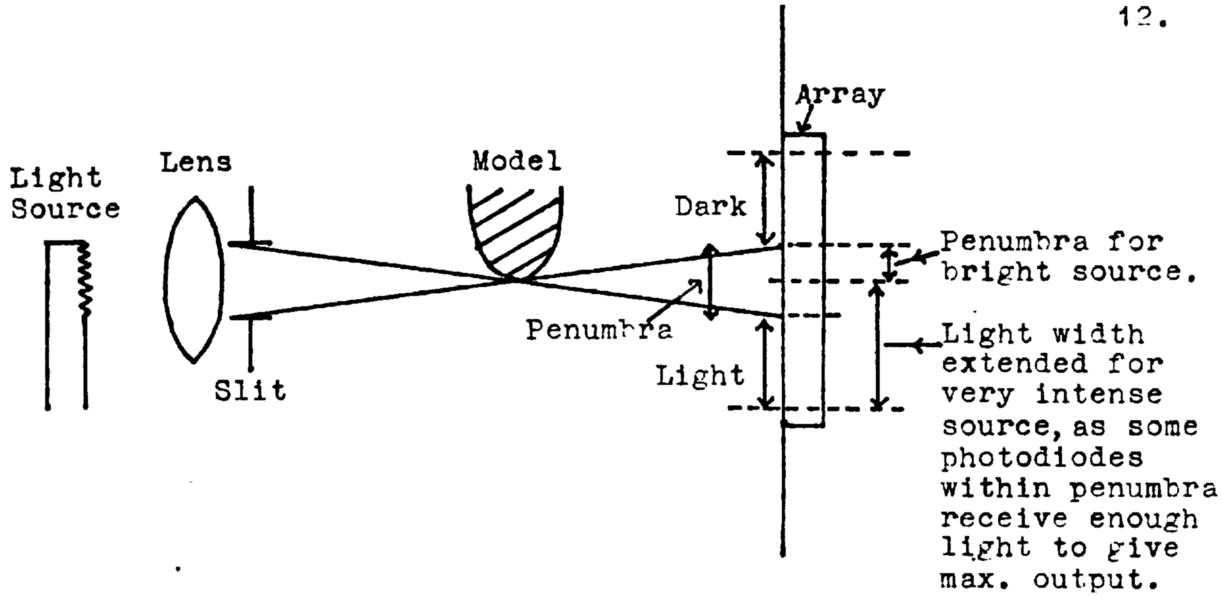


Figure 6. Narrowing of Penumbra by a very bright source.

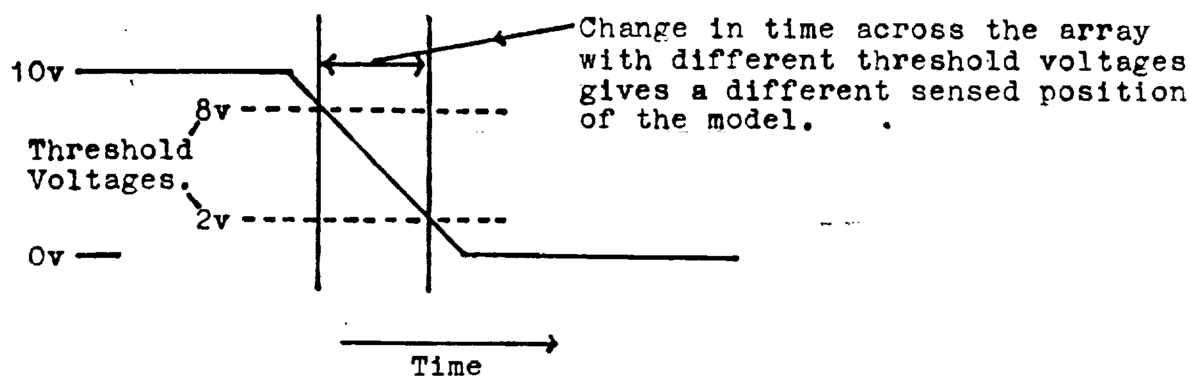


Figure 7. Effect of Transition Edge on Sensed Position of Model.

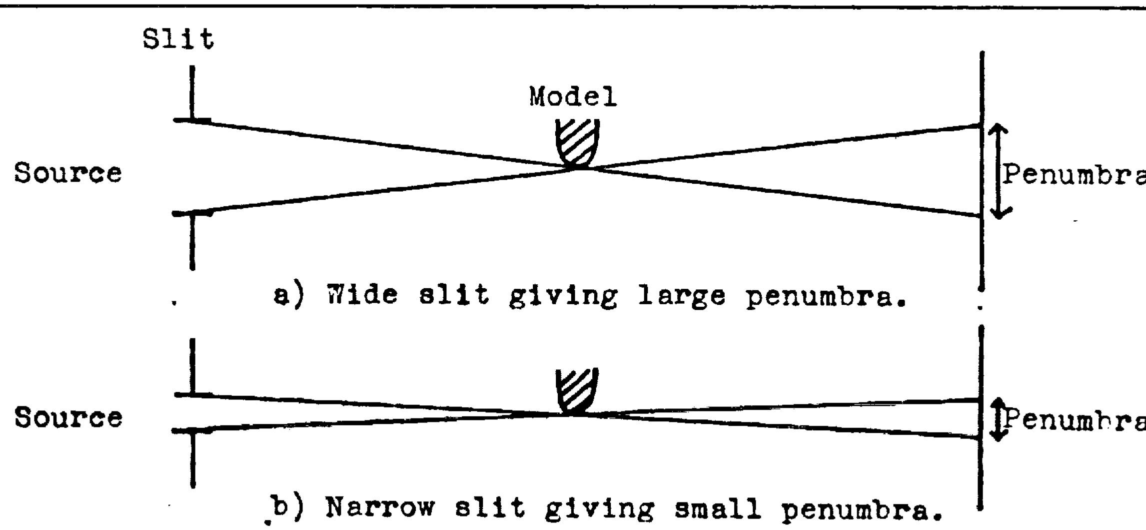


Figure 8. Relationship between Slit Width and Penumbra.

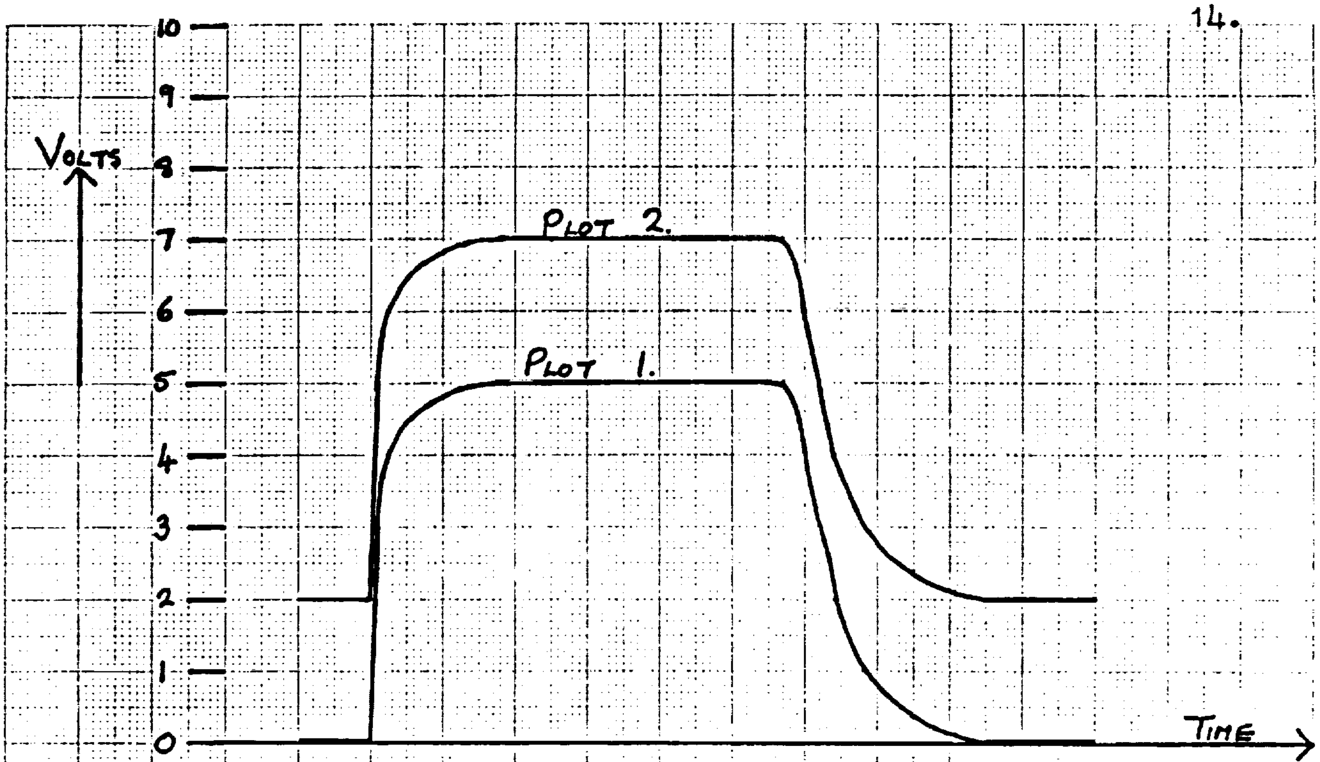
clear therefore that the maximum intensity of light possible should be used to give illumination 'in hand' for smoke tests.

(iii) The slit arrangement used for the photosensor lighting system will be used again for the array. This slit is made as narrow as possible to give an effective point source of light. The more intense the light source, the narrower this slit can be made and thus the smaller the penumbra is on the array. See figure 8.

3.2.2.Background Lighting

It was discovered that 'normal' background lighting in a room (i.e. not direct sunlight, but room lighting on, and reflections from outside light) can raise the unlit array output to as much as 2 volts. This background lighting now adds to the light from the source. Four waveform plots in figure 9 show the effect on the transition edge. In all of them the board preset is adjusted to give maximum 10 volts output. The first waveform shows the source intensity adjusted to give 5 volts illuminated video output with zero background lighting. The second shows the same source intensity but with 2 volts background lighting. The illuminated level is now 7 volts and the whole waveform has effectively been moved upwards by 2 volts. Both these two traces have transition edges which take the same time to fall. The second pair of waveform plots have the source adjusted to just give 10v output (with no background lighting). One waveform however has no background lighting, the other has 2 volts. The extra lighting makes the transition edge sharper but there are two reasons for requiring a 0v. unlit output:

(i) Results are not repeatable if the background level varies as say the sun goes in and out. One must therefore try and keep background lighting constant at some level, and the easiest thing to do is to try and hold it to give



Plot 1 : Intensity of light at 5v, Background lighting at 0v.
Plot 2 : 5v, 2v.
Plot 3 : 10v, 0v.
Plot 4 : 10v, 2v.

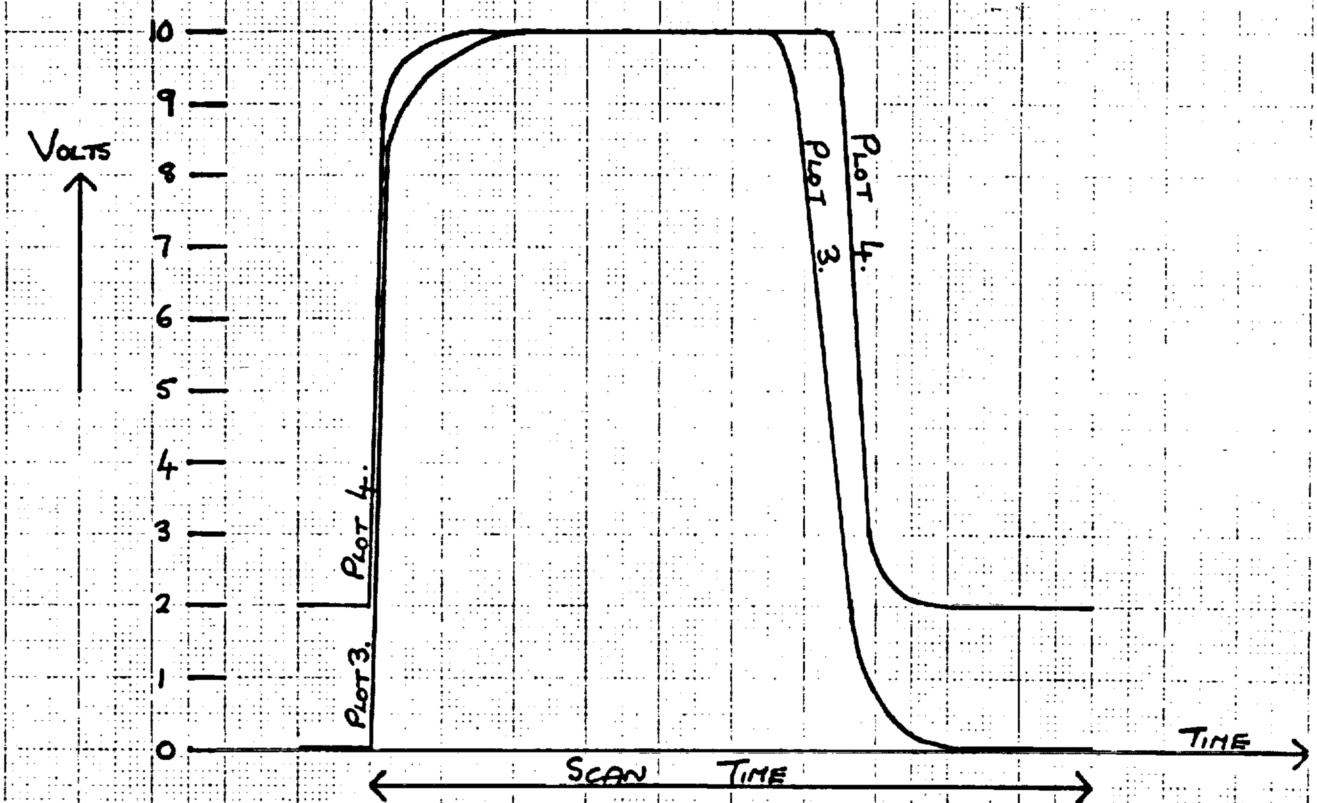


Figure 9. Transition Edges with Background Lighting.

zero volts output.

(ii) As discussed in the previous section, when smoke is inserted into the tunnel, the light output level comes down and the low voltage levels on the falling edge move least. Therefore it is desirable to use this part of the curve for the light to dark transition point and thus the background level should be kept to zero volts.

The solution to this problem was found in placing a short collar around the array to cut out most background lighting. This collar was about 4cm. long with a diameter of approximately 5cm. Its internal edges were grooved and painted matt black to cut down internal reflections. As long as the array was kept away from facing directly into the room lights or the window, this was found to be sufficient to keep the dark level to roughly zero volts. Ideally, background lighting will be kept as low as possible in any future system as the edge obtained from the video output using the collar was still not as sharp as that in a completely darkened room.

3.2.3. Focusing of Image

The bulb used for the photosensors had a very fine, closely wound filament. The filament is focused by the first lens to give uniform light output across the width of the sensors.

Conversely the headlamp bulb had a very coarse, loosely wound filament and when this was focused on the array, the pattern of the filament showed up as alternate light and dark patches! To get round this the lens was moved to half its focal length from the filament. This will produce a divergent source of light which may not have completely uniform light intensity across the length of the array. This is not as important to obtain with the array as with the photosensors. However the filament pattern on the array was now 'blurred out'.

3.2.4. Wavelength of Light Source

No mention has been made so far of the spectral response of the photodiode array. A graph of this is given in appendix 2 showing that the peak response of the array is in the infra red. For light at the visible wavelength only, the responsivity of the array is roughly a half of its maximum. No figures were obtained as to the infra red content of the halogen headlamp bulb used but consideration of this should be given in any future system especially with regard to inserting smoke in the tunnel.

3.3. ILLUMINATION ARRANGEMENT FOR ARRAY

The arrangement finally used with measurements is shown in figure 10.

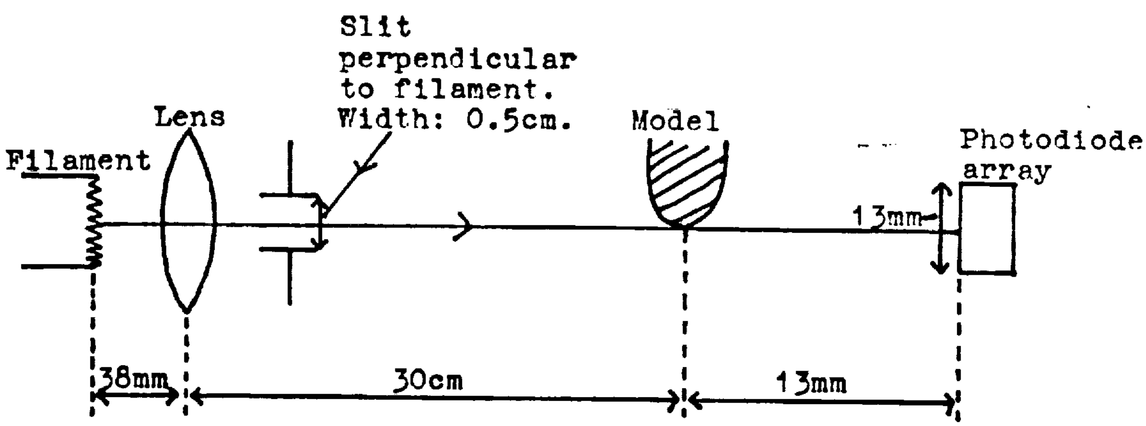


Figure 10. Illumination Arrangement for Array.

Assuming the light to be a point source and knowing the photodiode array length, the maximum movement of the model detectable with these dimensions can be estimated. The array is 13mm. long, so a movement of the model through 8.125mm. will cover the entire array length. The array is 512 elements long so the resolution is 0.0159mm. The resolution can be made smaller (i.e. better) by moving the model towards the lens, or the maximum detectable distance can be made larger by moving the model towards the array.

4. CIRCUIT DESIGN

The video output of the I.P.L. board is to be converted to a zero to 5 volt analogue signal, the voltage being proportional to the position of the shadow along the array i.e. 5 volt output if the array is completely illuminated, zero output if the array is covered. It was decided to produce first a digital binary output, then convert this using a D-A converter to give an analogue output. A block diagram of the circuit is shown in figure 11 and the initial circuit diagram of the comparator, counter and latches in figure 12. A complete circuit diagram of all additional circuitry designed is shown in figure 15 at the end of this chapter. Each circuit block will now be considered separately:

4.1 THE COMPARATOR

A comparator is used to threshold the input and to determine an arbitrary voltage where the video signal goes from light to dark (or vice versa). The comparator is designed to be variable over the threshold range: 1 volt to 9 volts, so that the optimum level can be selected depending on the lighting conditions.

4.2. THE COUNTER

There is available from the I.P.L. board, the clock signal and pulses which start the scan across the array. It would be convenient to use the board clock to clock a counter which is free to run until the comparator output goes low i.e. when the array goes dark. This number can then be run onto latches and the counter reset to zero at the end of the scan. Thus the latches will be reset once every scan. The circuit employed is going to try and use the scan start A pulse (ssA pulse) to both enable the latches and the counter without losing the first bit of

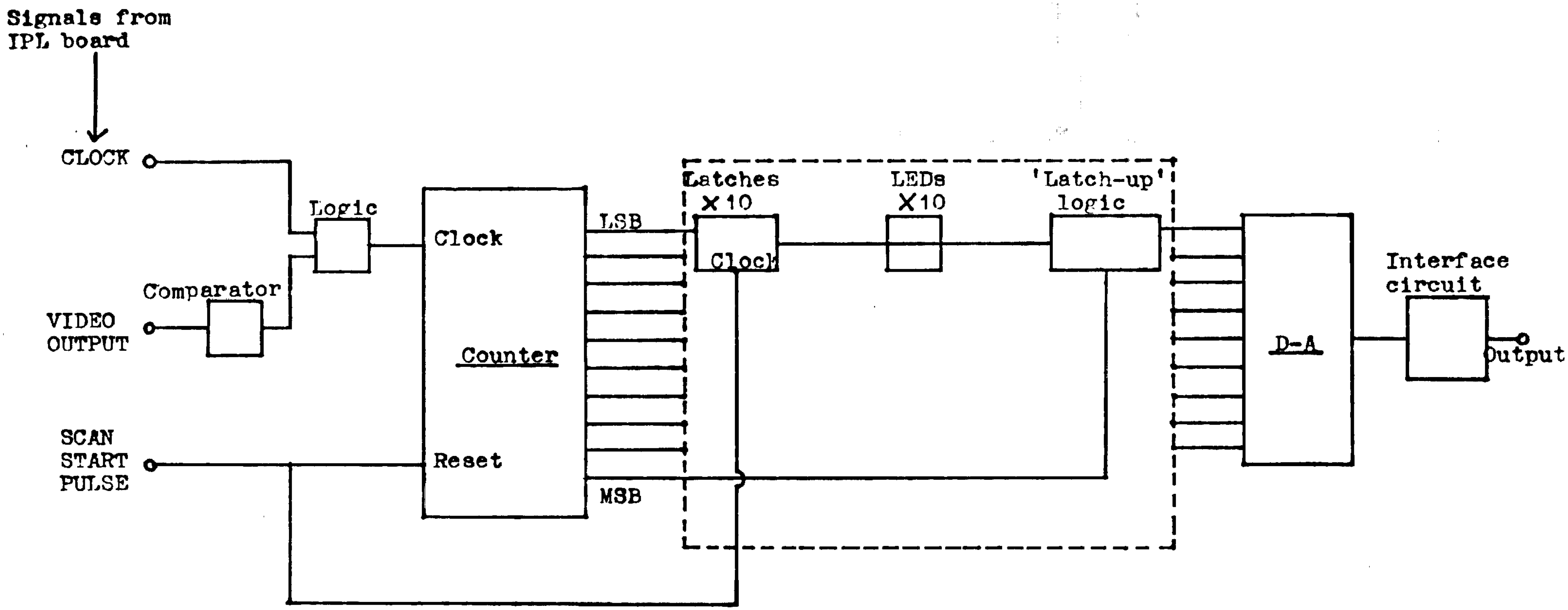


Figure 11. Block Diagram of Circuit.

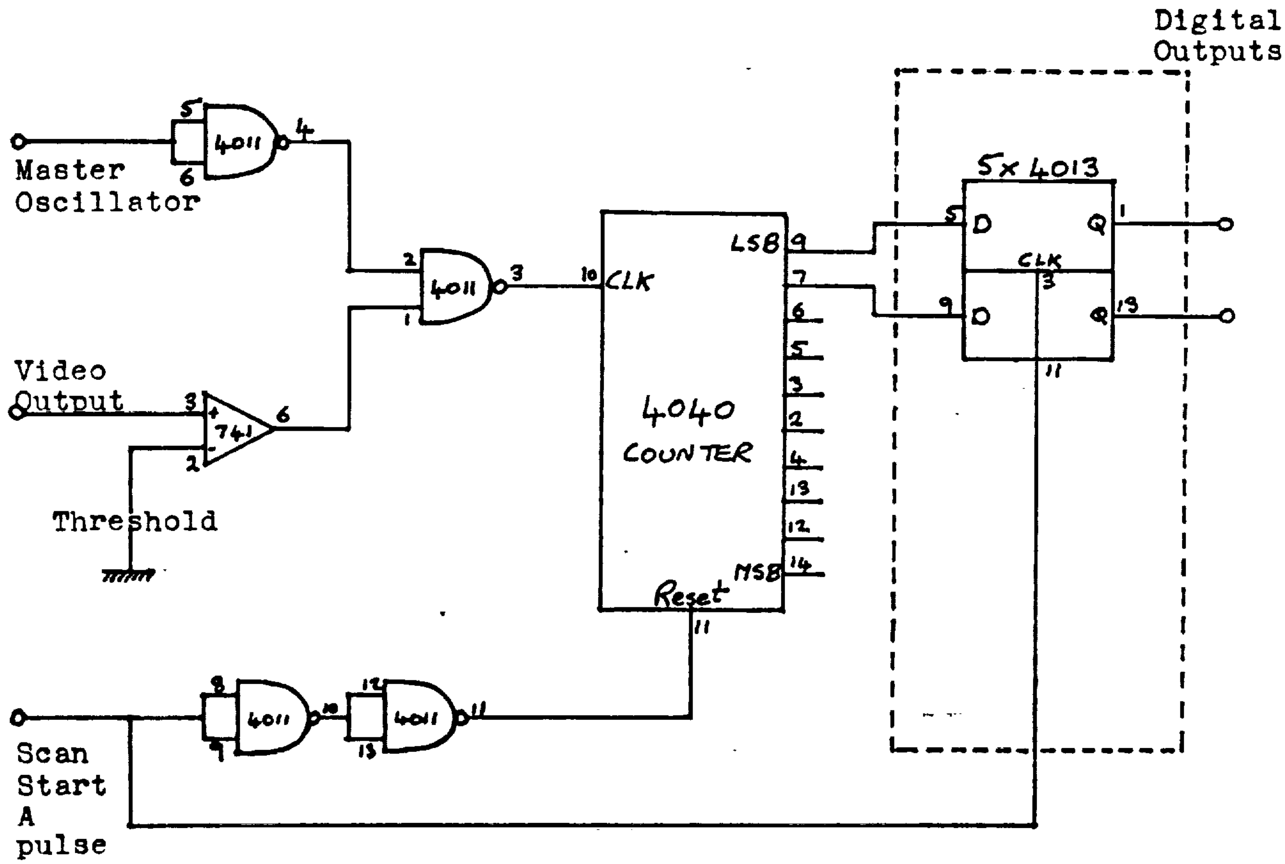


Figure 12. Initial Circuit Design up to Latches.

video information. In order to do this the relative position of the scan start pulses and the clock must be considered. The waveforms are shown in figure 13.

The counter counts until the comparator output goes low (and thus the clock input stays high). The ssA signal is connected straight to the clock input on the D type latches. These transfer data to their output on positive edges so this is done at the beginning of the ssA pulse (and takes approximately 25ns). The ssA signal is connected to the reset pin on the counter via a delay of two nand gates (about 50ns). The reset has an active high input so the counter is now reset to zero and held there until ssA goes low.

If the beginning of the array is illuminated, the comparator input will go high at the beginning of the ssA pulse, thus enabling the counter clock input. The clock to be used is the master oscillator (figure 13) which is high for roughly twice the time that the ssA pulse is. So when the ssA pulse goes low the counter clock which is negative edge triggered will start counting on the first element.

When this circuit was tested it was found that in fact the counter was not being reset. This was due to the output from the two nand gates delay having a slow rise time and appearing to not reach the full +15 volts. One solution of this is to insert a schmitt trigger after the nand gates to sharpen up this pulse. In this case it was decided to use the ssB pulse to reset the counter to save on using another integrated circuit. This does however mean that the first photodiode on the array is not used. This is not important for this system, but if for instance two or more of these arrays are to be used placed serially to give a larger scan length, then it could be important to utilise all photodiodes.

There is a space of 8 clock pulses between the 512^{th}

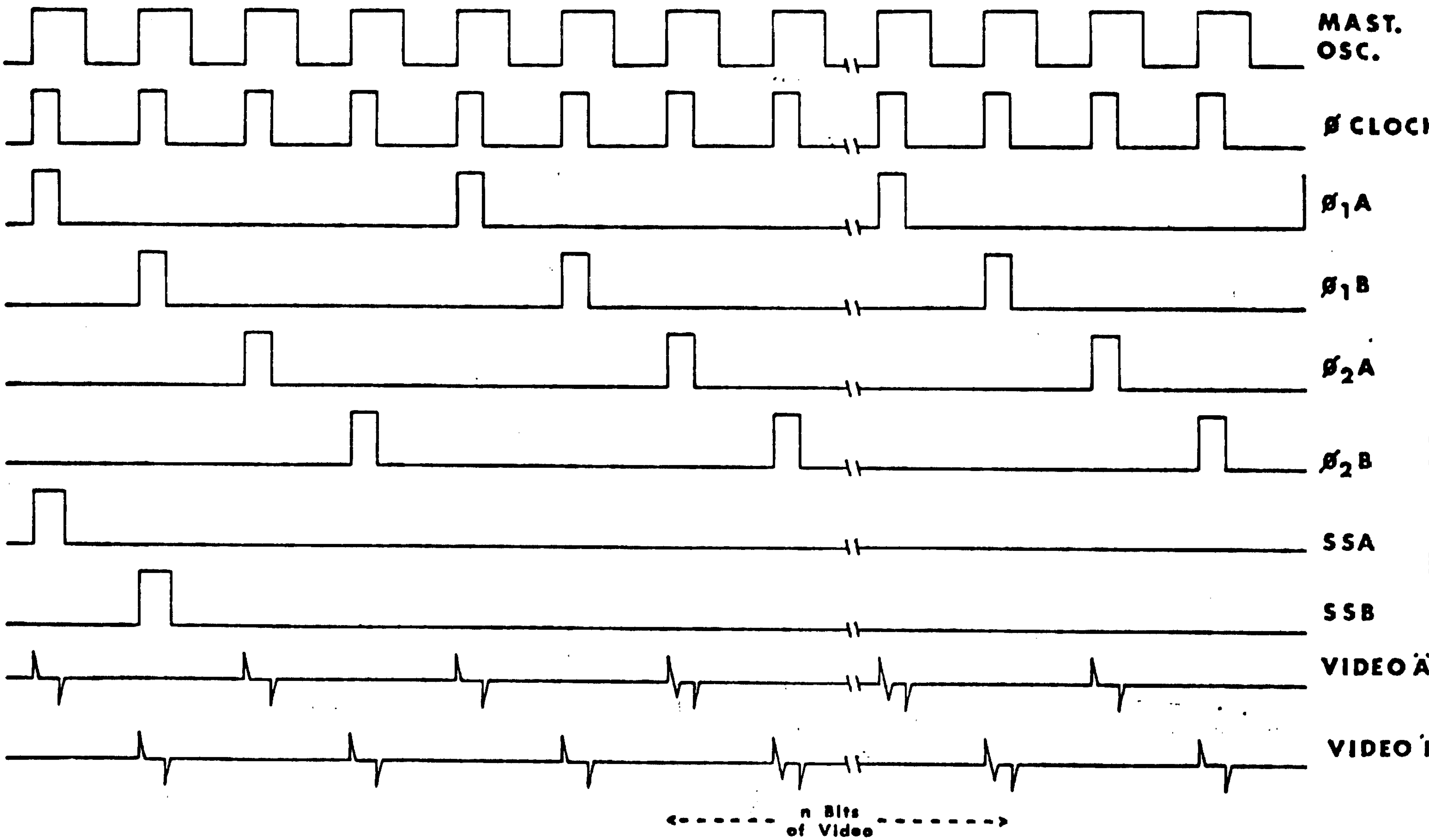


Figure 13. Waveforms produced by IPL board.

photodiode being clocked and the ssA pulse. So when all the photodiodes are illuminated, the counter in fact counts to 519 since the video output has a slow fall time and the comparator does not detect a gap of 8 bits.

4.3 THE LATCHES

The 4013 D-type flip flops were the only suitable memory circuits available. The latches have to store the information from the counter between successive ssA pulses. During the ssA pulse this information must be clocked onto the outputs and stored until the next pulse. These latches require just one input. The 4044 latches require separate set and reset inputs which is not suitable for use here. The optimum latch to use is the 4042: quad clocked D-type which has 4 D-type latches per chip requiring no separate set and reset inputs. This would halve the 'chip count' for the latches.

4.4. THE LEDS

Ultimately the wind tunnel will be controlled by a computer which will require the digital information on the output of the latches. For the moment this digital information was shown visually as a binary readout of position on 10 leds. These required 30mA each and the driver circuit is shown in figure 15. This circuit can supply up to 26mA. 10 leds. at maximum require 260mA and on the prototype board this supply is delivered from a separate +15 volt supply.

4.5. 8 BIT D-A

512 elements indicates a 9 bit D-A converter is required. A 10 bit one was ordered but a long delivery time was quoted. So at first a readily available 8 bit D-A was used (RS: DAC 0800) and the least significant bit was discarded, thus halving the resolution of the array.

The circuit diagram is shown in figure 14. This D-A has a typical settling time of 100ns. It requires a reference current (which controls the output current) and this must be fed by a stable reference voltage. In this case the reference voltage was taken from the +15v. supply using two decoupling resistors and two capacitors. The addition of an op-amp to the D-A provides a low impedance output, and the output voltage swing can be adjusted both in maximum amplitude and range (by use of the offset null pot.).

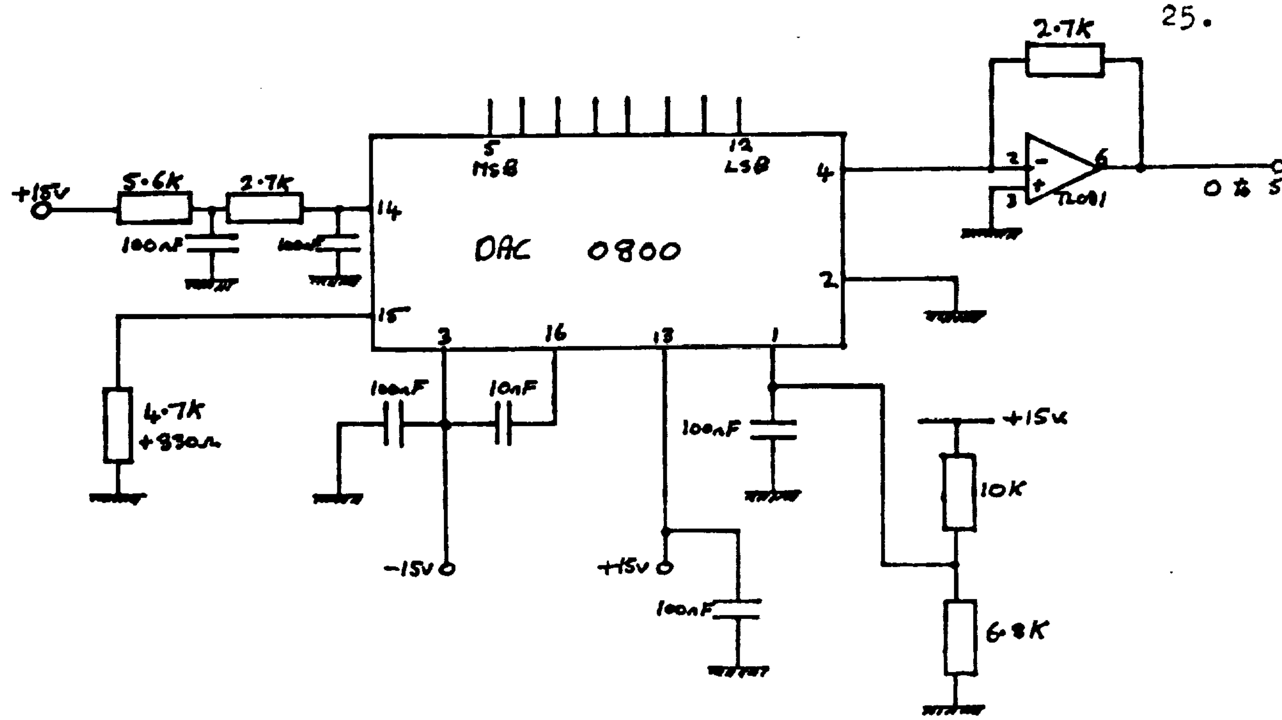
4.6. 10 BIT D-A

Shortly after the 8 bit D-A had been connected, the 10 bit D-A arrived. Appendix 3 gives the information sheet supplied with it. The circuit diagram is shown in figure 14 and calculations are given in appendix 3.

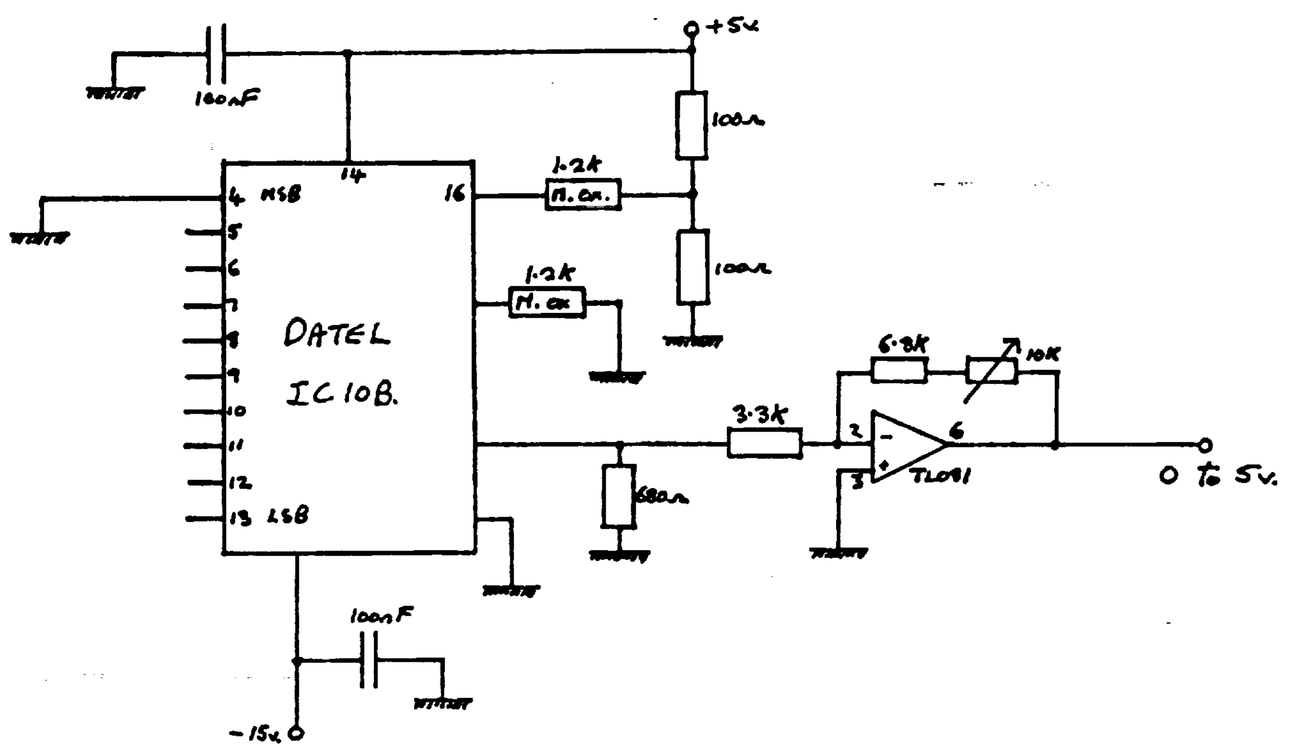
A separate 5 volt source was used for the D-A supply and current reference. This is not necessary and could be taken from the +15 volt source, suitably divided down and decoupled, if required.

4.7. 'LATCH UP' GATES

It was stated in section 4.2 that the counter counts to 519 when the array is completely illuminated. Thus when using the 8 bit D-A the output was a maximum at 511 and dropped to zero at 512 to 519. Although in the test wind tunnel it is not intended to operate the sample models at the extremes of the display, this effect will make the placing of the models in the first instance in the tunnel, difficult. When the array is completely lit, the control system will react as if it is completely dark since the D-A output is zero. The magnetic field will therefore be attempting to pull the model up as hard as possible. As the model is lowered in, the D-A output will suddenly



8 Bit D-A.



10 Bit D-A.

Figure 14. D-A Circuit Diagrams.

swing to maximum, thus the magnetic field will drop and the tendency will be for the operator to push the model out of the tunnel before reacting to the sudden change in field.

This situation is also not desirable since when the magnetic coils are switched on and no model is in the tunnel, one prefers them to be carrying just quiescent current rather than the 35 to 40 amps. maximum they do when the input from the sensor is zero. It was therefore decided to latch the output of the 8 bit D-A at its maximum when the bit count exceeded 511. This figure was chosen as then the 10^{th} binary bit could be used to drive the latches.

The method used was to insert dual input 'or' gates between the outputs of the D-type flip flops and the inputs to the D-A (see figure 15). The other input of all of these gates was connected to the 10^{th} bit so when this goes high all outputs of the or gates (and thus inputs to the D-A) are high and stay high until the 10^{th} bit goes low again.

When the 10 bit D-A replaced the 8 bit, it was considered whether to remove the or gates, since the 10 bit can cope with the number 519. In fact the or gates were left since, if ever the I.P.L. board is used with a 1024 element array, the 10 bit D-A can still be used and the 11^{th} bit from the counter used to control the or gates.

4.8. INTERFACE CIRCUIT

The existing control system consists of several amplifiers and summers using LM308 op-amps. The interface circuit, which goes between the output of the D-A and the input to the existing control system, was built on a card which was inserted into the control system rack. The circuit is shown in figure 15.

A switch was incorporated to change the input of the heave control loop from the photosensor to the photodiode array. The point where the D-A signal is applied requires an inverse signal to what was originally thought so an op-amp was built with a gain of -1. In use it was discovered that the model was not steady. It 'jittered' occasionally due to transients and quantisation effects from the D-A output being greatly amplified in the control circuit. Thus a 0.2μF capacitor was added in parallel with the feedback resistor of the op-amp, thus giving an inverting filter with a roll off frequency of 79.5Hz.

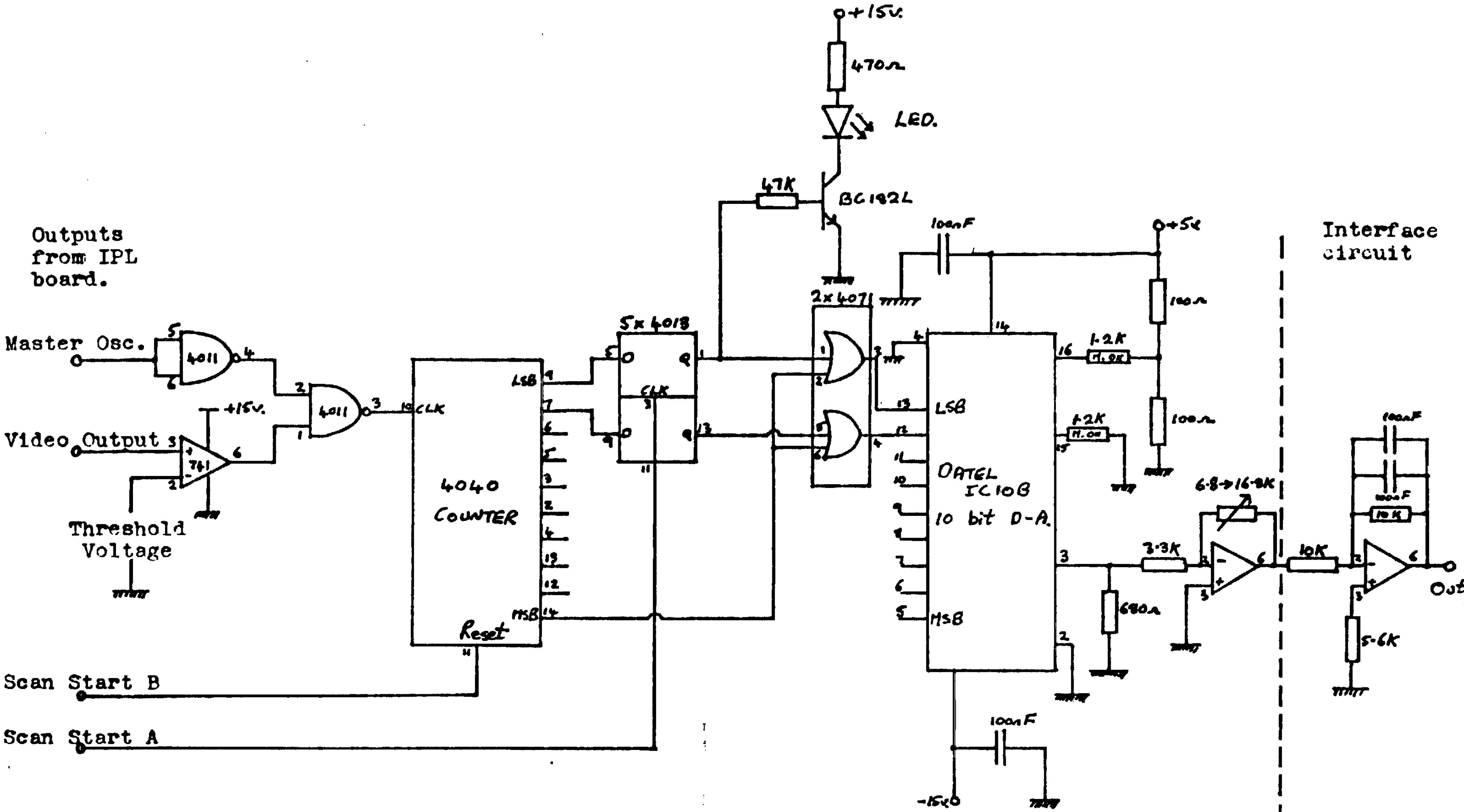


Figure 15. Complete Circuit Diagram.

5. OPERATION AND TESTING

No problems were experienced in floating a model using the array, and switching between the two sensing systems could be carried out while the model was in the tunnel with no detectable difference in performance with either system. This section is divided into two parts. The first discusses calibration tests, the second fogging tests in the tunnel.

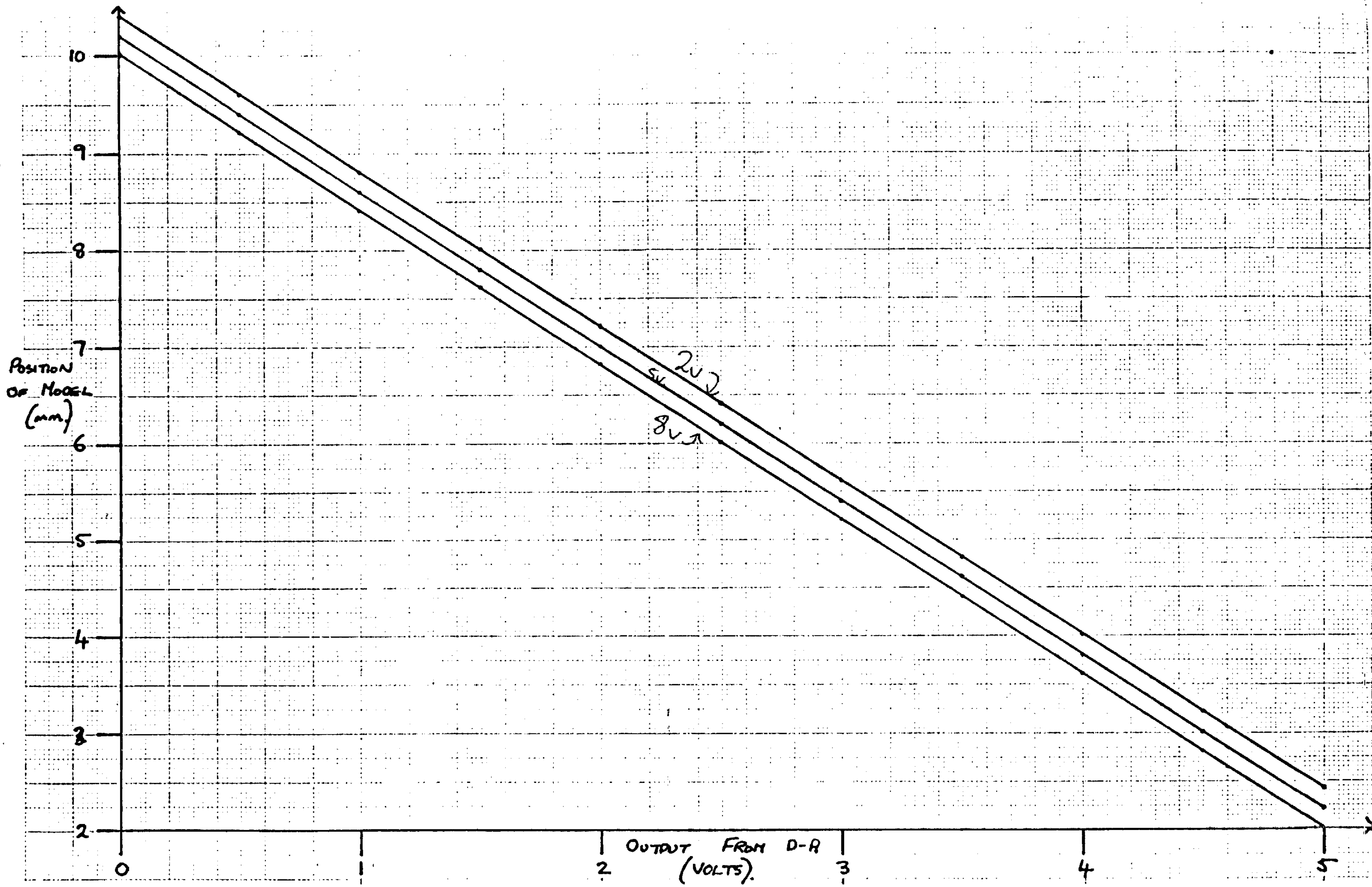
5.1 CALIBRATION TEST

The first test to be carried out was to calibrate the heave position of the model with the output of the D-A, and make sure that they had a linear relationship. (The existing photosensors were used to control pitch motion). In order to do this, an optical bench was placed along the bottom of the tunnel. Mounted on this was a lens holder which could be moved up and down with a vernier adjuster giving readings accurate to 10^{-2} mm. The top edge of the lens holder represented the model and intercepted the beam of light as it was moved up and down.

In the test the scanning frequency used was 1 KHz. (i.e. D-A being updated at a frequency of 1 KHz.). The video illuminated output was 10 volts and background lighting gave about 10mV. Graph 1 shows three calibration tests for the op-amp threshold voltage set at 2v., 5v. and 8v.

The relationship between distance and output is linear in all three cases and the total movement sensed by each of them is 7.92mm.

The relative difference in position of the three lines is to be expected. If one refers to figure 7, it can be seen that the three threshold voltages used are at different points up and down the video output curve. Graph 1 gives approximately 0.2mm in difference between the 2v. and 5v.



GRAPH 1. Photodiode Array Calibration Tests.

and between the 5v. and 8v. lines. (The difference of 0.2mm is the same if one refers back to figure 5 and considers the width of the high output in the third waveform at the different threshold voltages).

5.2 SMOKE TEST

One of the most important reasons for investigating the use of the photodiode array in the tunnel was that by using the principle of detecting the edge of a shadow, one should be able to insert smoke without affecting position readings. Therefore testing of this capability was regarded as important.

The smoke was 'simulated' by layers of polythene cut from polythene bags. These were placed directly over the collar, i.e. only about 4cms. from the array. This is actually the 'least sensitive' position for the polythene as the light will be less scattered by it placed here when it reaches the array as opposed to the polythene for instance being placed directly over the source.

For these tests the bulb was run at 50 watts and the input threshold was set to the minimum level possible: 2 volts. One measuring system was used to test the other. However two preliminary sets of results had to be taken first:

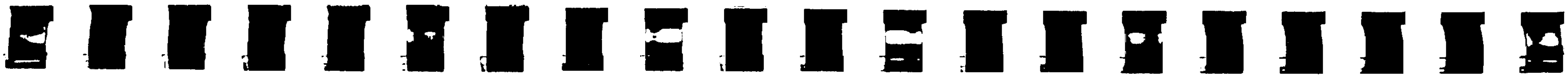
(i) The photosensor system had to be calibrated as was the photodiode array in the last section. This is shown in appendix 4. Only about half the range was covered as this was all that was required.

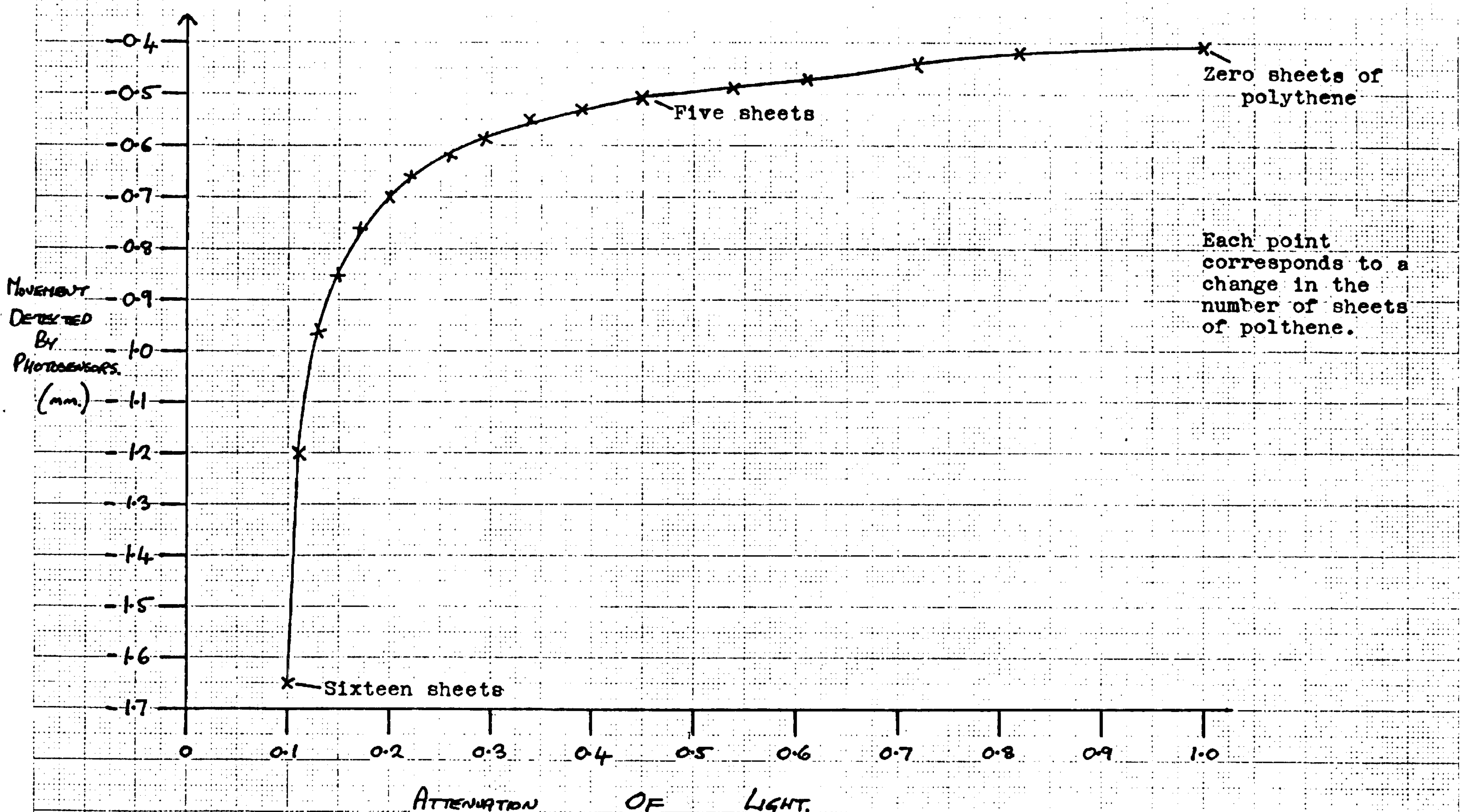
(ii) The light attenuation by the layers of polythene had to be calculated. This was done by placing the polythene over just one of the photosensors and these results are shown in appendix 4. 2.44 volts is equivalent to maximum light and zero volts to complete darkness. An additional linear scale has been added with 100% corresponding to 2.44 volts and 0% corresponding to zero volts - this gives the light attenuation. In the first test the photodiode array controlled the heave motion and the layers of polythene were placed over it. As this was done the output of the photosensors gave a reading of the movement in position of the model and this is plotted in graph 2 as position against attenuation of light.

Sixteen sheets of polythene were placed over the array before the model went out of control. The graph shows that at 50% of original light the model has moved by 0.218mm and even at 30% by only 0.436mm. To put this in perspective, 0.218mm represents only 2.7% of the total length of the photodiode array and thus represents movement of about 14 photodiodes only.

With the light level below 30% of original the model starts to move much further and eventually goes out of control below 10% of the original light level.

In the second test the two sensing devices were used the other way round, with the photosensors controlling the heave motion and the photodiode array indicating the movement while the polythene was placed over both of the photosensors. As expected, the photosensors were far less immune to the polythene. With one layer of polythene, the model moved by 1.6mm., with two by a further 2.15mm. and with three it went out of control! These results are not plotted on graph 2!





GRAPH 2. Movement caused by Light Attenuation using Array.

6. FURTHER WORK

Much still remains to be investigated about the use of the photodiode array, and points raised by this report are considered in this section.

(1) Only one array has been used so far. The next stage is obviously to set up two arrays to control pitch as well as heave.

(2) To sense a larger range of movement it may be required to extend the 512 element array to a longer one. The I.P.L. board will take a 1024 element array giving twice the existing sensing length. The 10 bit D-A in use can be operated with a 1024 array since at present one of its bits is not being used.

(3) It may be important in future to access the first photodiode of the array which at present is being missed. This could be used if suggestions in section 4.2 are carried out. Alternatively the 'end of scan' pulse could be used from the photodiode array (on pins 1 and 15) and this used to open the latches and reset the counter during the 8 pulse gap at the end of the scan.

(4) It is not known how much attenuation of light will be caused by smoke in a wind tunnel and thus whether the results obtained with polythene are acceptable.

(5) This photodiode array is more responsive to infra red light than visible light. Since scattering of light is very low in the infra red spectrum, this will almost certainly be a method of overcoming the smoke problem. This is regarded as a most important point.

(6) It is not known what sort of conditions will be encountered in any future wind tunnel but no consideration has been given to the effect of dirt on the array window.

It is suggested that the wind should keep the window clean, and from experience, small particles of dirt, fluff and hairs do not affect the output.

(7) The temperature inside wind tunnels can get very low and it is not known if this will affect the photodiodes' response. One would suspect that impurity levels with energy levels between the valence and conduction bands would be frozen out and so there will be no effect as long as one works with light frequencies greater than the band gap.

(8) Again, the photodiodes may react to very strong magnetic fields such as will be encountered and this must be investigated.

(9) An optical reflective target system was mentioned in the introduction, (see appendix 1). This can be looked into with a view to using models that are not specially shaped.

7. CONCLUSIONS

It has been shown that photodiode linear arrays can be used to detect the position of models in a wind tunnel.

The method of thresholding the video output signal from the array and converting it to a binary digital then an analogue signal has proved satisfactory. Much thought however has to be applied to the optical system to obtain a sharp transition from light to dark on the array.

The output of the system has a linear relationship with the position of the shadow on the array. It has also been shown that the photodiode method is relatively immune to smoke in the wind tunnel, the light intensity having to be cut to below 10% before the model goes out of control. Further investigations are required concerning this, in particular, the capability using an infra red source.

8. REFERENCES

1. Fry P.W. — Applications of Self-Scanned Integrated Photodiode Arrays. Radio and Electronic Engineer 46(4), 1976, 151-160.

2. Vann M.A. — Self-Scanned Photodiode Arrays - Charactistics and Applications. Optics and Laser Technology. 6, 1974, 209-218.

3. Fry P.W. — Silicon Photodiode Arrays. J. of Physics (E). 8, 1975, 337-349.

4. Dyck R.H. — A New Self-Scanned Photodiode Array. Solid State Technology. 14(7)1971, 37-42.

5. Integrated Photomatrix Ltd. — Handbook for: 'IPL M Series PDA System.'

APPENDIX 1

OPTICAL REFLECTIVE TARGET SYSTEM

This system involves putting optical targets on the wind tunnel model. These targets have a sharp transition from a highly reflective surface to a matt black non-reflective area and when light is shone at this transition edge it will cause a shadow on the photodiode array - see figure 16. The advantage of this method is that there will be greater flexibility in the shape of the models that the wind tunnel can accommodate.

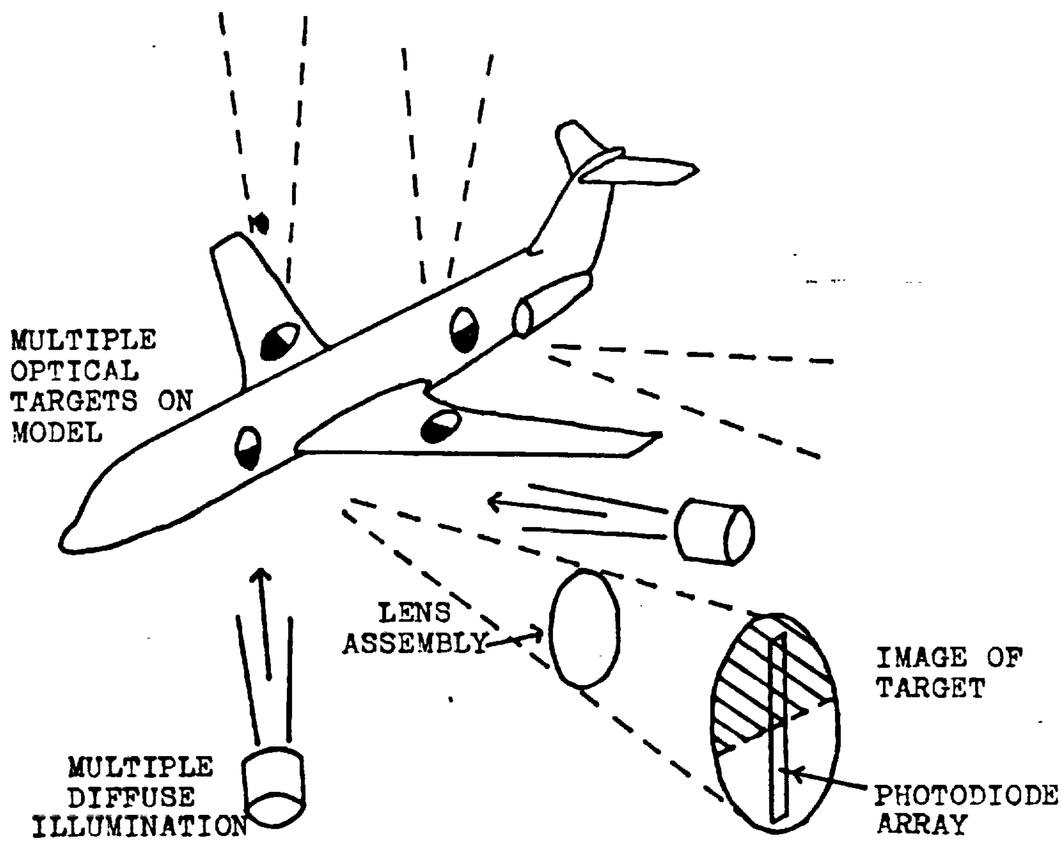


Figure 16. Multiple Optical Target System.

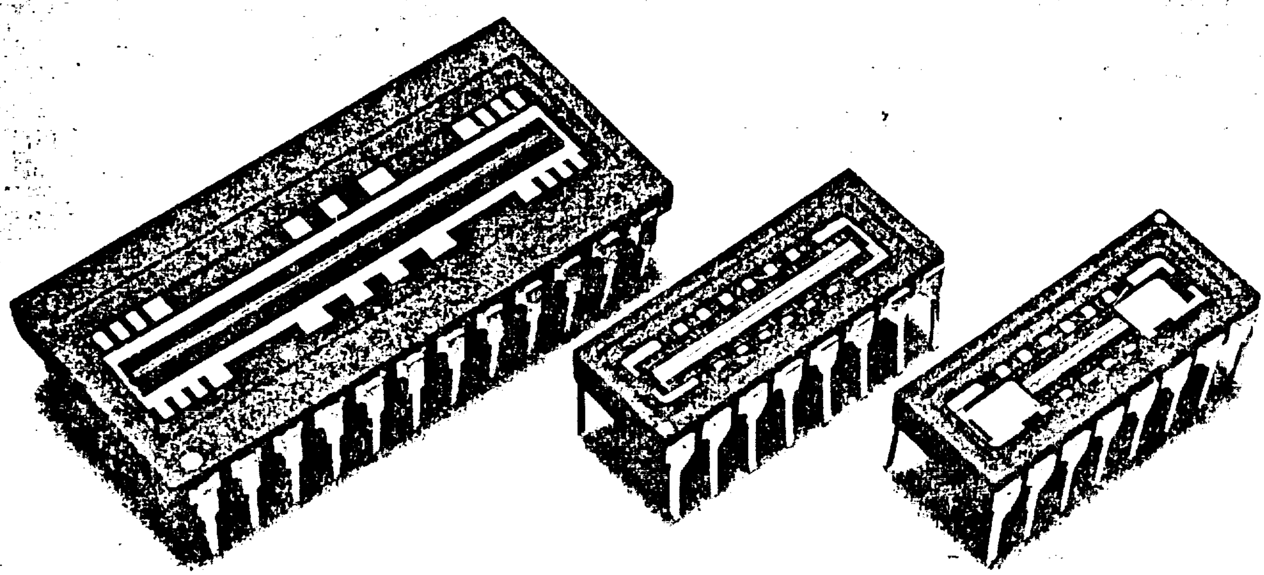
APPENDIX 11

I.P.L. INFORMATION SHEET ON PHOTODIODE ARRAY

IPL M Series Array Data

information sheet

IPL



Features

- Arrays of 256, 512, or 1024 on .001″ centres
- Scan speeds to 10 MHz
- Recharge mode signal output.

Introduction

The IPL M-series of arrays are silicon self-scanned linear photodiode arrays with integrated scanning circuitry included on the same chip. The arrays are manufactured in three different sizes, 256 elements, 512 elements and 1024 elements. The diode pitch is .001″. Two sizes of diode aperture are available to enable users to select the aperture width best suited to their application.

General Description

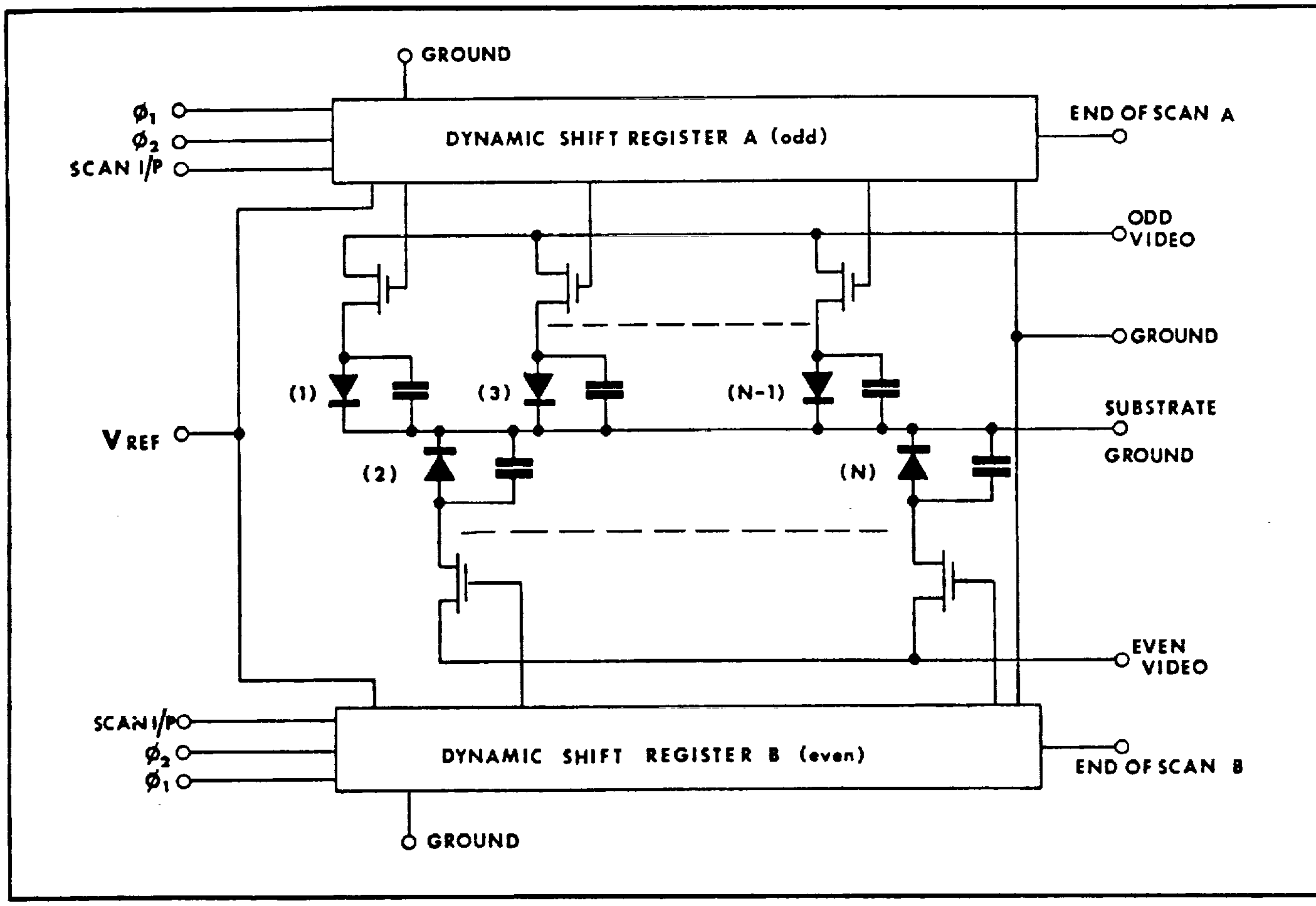


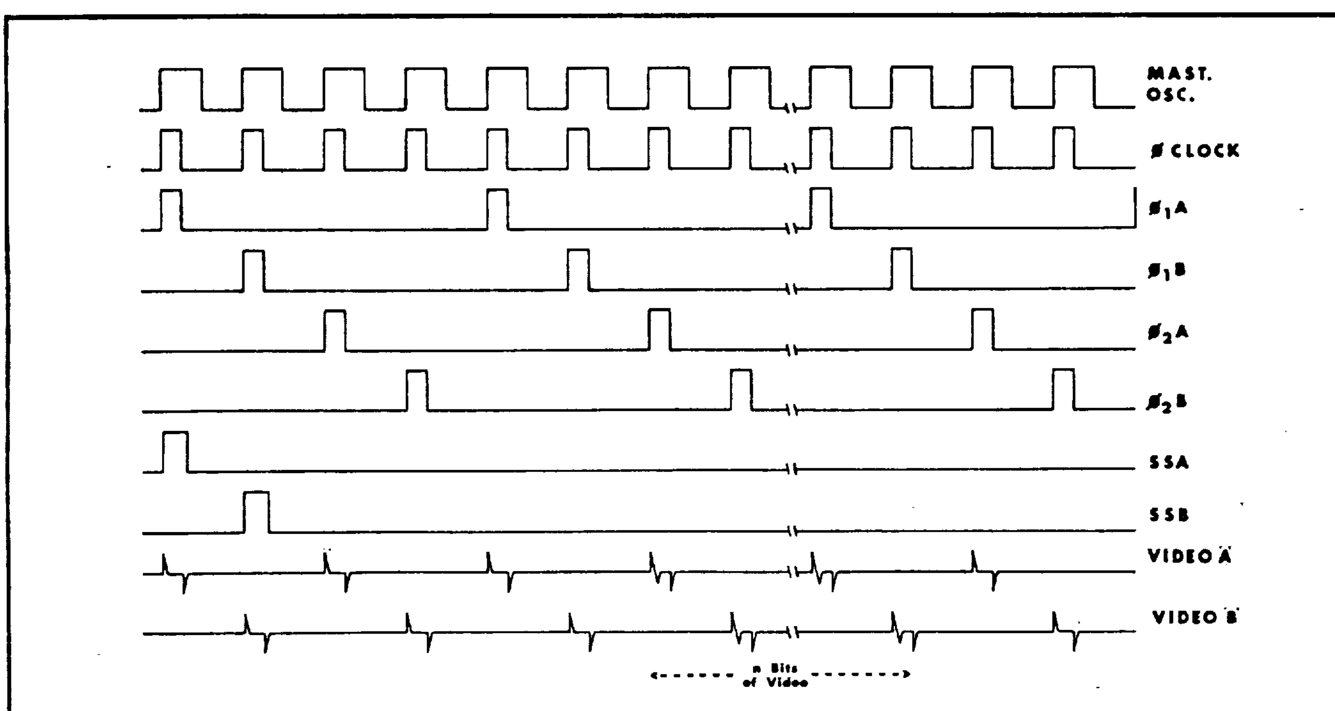
FIG 1

A simplified circuit diagram of the M-series array is shown in Fig. 1.

The Shift Register

FIG 2 **TTL Timing Logic**

The Photodiodes with their associated parallel storage capacitors are connected through MOS transistor switches to a common video output line. The switches are turned on and off in sequence by a shift register. Each device contains two shift registers, each register accessing alternate diodes. Each shift register is driven by two non-overlapping clock



pulse trains Ø1 and Ø2. The array scan is initiated when a scan start pulse is applied at the scan start input terminal The scan pulse is propogated through the register alternatively by Ø1 and Ø2 A TTL timing diagram of the clock pulses is shown in Fig. 2.

The shift registers can be operated in several different ways. By clocking the two registers alternately and connecting the video outputs in parallel a serial stream of video information is obtained representing every diode in the array. Alternatively, by clocking the two registers in parallel, and processing the separate video outputs each video output will represent the odd and even diodes respectively. A third alternative is to operate the registers simultaneously and connect the video outputs in parallel. This gives the effect of a .002 inch pitch array with half the total number of diodes being accessed. A reference voltage termed V.ref. must be applied to the shift register at all times in order to operate it. This voltage is nominally - 8.5V in value.

When all the photodiodes in the array have been sampled, an output pulse appears at the end of the scan terminal which is provided for each shift register. The end of scan pulse appears two clock periods after the final diode is sampled. The pulses are referenced to the end of scan ground terminal and this needs to be connected to ground. A buffer circuit for the end of scan is shown in Fig.3.

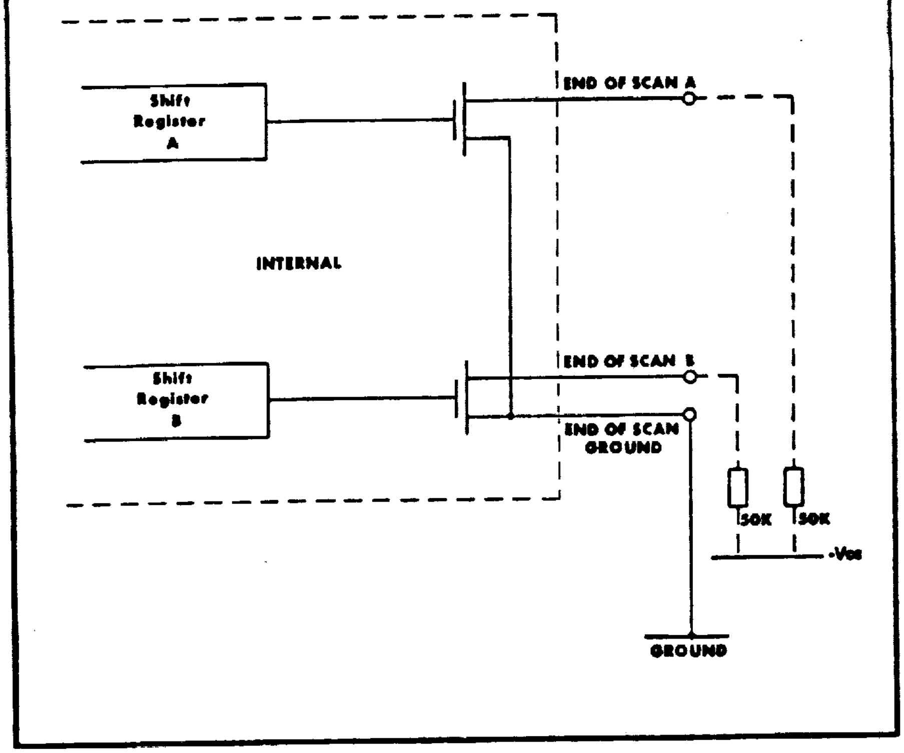
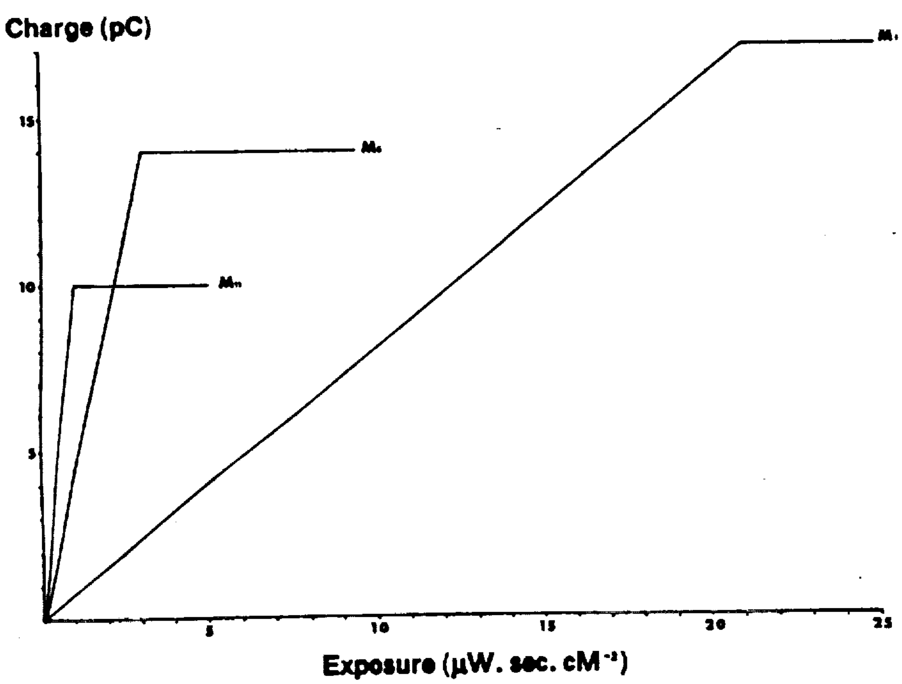


FIG 3

The Photodiode Array

FIG 4



The Photodiodes in the M array operate in a reverse bias, light integration mode. In this mode, the initial scan pulse propagated through the shift register causes each photodiode in turn to be charged to the negative potential applied to the video output terminal. During the period before the subsequent scan pulse, termed the integration time, the photodiode loses an amount of charge proportional to the total amount of light incident upon it. The subsequent scan pulse recharges the photodiode to the video output terminal potential. The amount of charge necessary to restore the photodiode to this potential represents the video signal. Hence a readout of charge proportional to light intensity is obtained.

The output charge is directly proportional to the exposure, exposure being defined as the light intensity multiplied by the integration time. A graph of the output charge against exposure is shown in Fig.4.

Video Processing

The video output of the M array is a serial train of charge pulses. to process these charge pulses IPL recommend the use of an integrator with sample and hold circuits to produce a d.c. referenced boxcar output waveform. IPL produce circuit boards to drive and process the output signal from the M arrays. The boards are sold as an assembly called the MPDA.

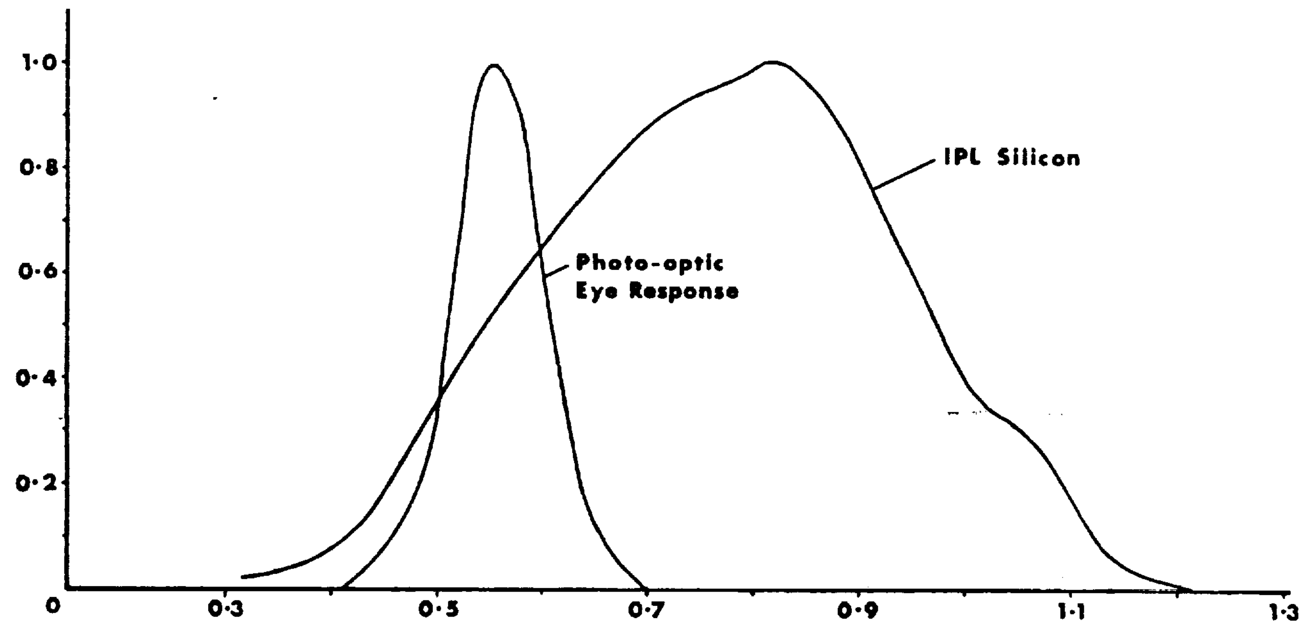
The video processor used in the MPDA allows optimum performance from the array to be obtained in terms of the signal to noise ratio.

Spectral Response and Responsitivity

The spectral response of the M arrays is shown in Fig.5. The response extends from the near ultra-violet to the infra-red region of the electro-magnetic spectrum. The peak response occurs near 820nm.

The responsivity figures given in the specification section are mean values. There is some variation of responsivity along the length of the array caused by the manufacturing processes used to fabricate the array. However, these uniformity variations also depend upon the particular light source used with the array. Tungsten light sources contain a high proportion of infra-red light to which the array is very sensitive. Uniformity variations are proportionally worse at infra-red wavelengths than visible. If light at the visible wavelength only is used, the responsivity variations are approx. 50% of the figures quoted in the technical specification.

Relative Response FIG 5



Signal to Noise Considerations

The maximum signal to noise ratio that can be achieved with the M arrays depends on the output signal processing used. Using the MPDA system, a signal to noise ratio of 400 is typically obtained with a 512M array. This figure is the ratio of peak output signal level to r.m.s. noise, including Fixed-pattern noise.

This noise contains three components. Dark leakage current non-uniformity, fixed pattern noise and thermodynamic noise. Dark leakage current is temperature dependant and only becomes significant at either temperatures above 30°C or integration times in excess of 40ms. Fixed pattern noise is dependant on the shift register drive waveforms, and can be cancelled in the MPDA. The last component, thermodynamic noise, is the random non-repetitive fluctuation which is superimposed on the dark signal. This cannot be removed by the signal processing; however, it is negligible compared with the noise in the signal processing circuitry for all normal applications.

Mechanical Details and Pin Connections

Pin Connections

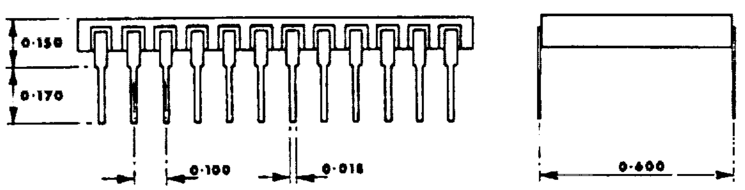
256M 512M 16 lead DIL

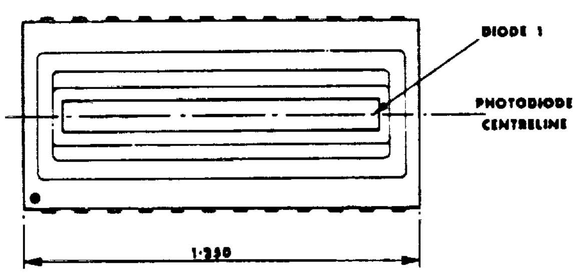
Pin No	Function
1	End of Scan A
2	Screen
3	V ref (both sides)
4	Ø2 A
5	Ø 1A
6	Scan start A
7	Video A
8	Screen and substrate
9	Screen and substrate
10	Video B
11	Scan start B
12	Ø 1B
13	Ø 2B
14	Shift register ground (both sides)
15	End of scan B
16	End of scan ground

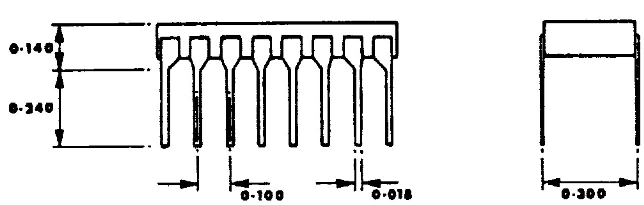
1024M 24 lead DIL

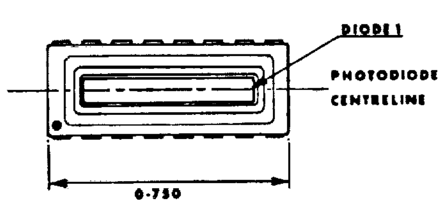
Pin No	Function
1	End of scan A
2	Screen
3	V ref (both sides)
4	N/C
5	N/C
6	Ø2 A
7	Ø1 A
8	N/C
9	Scan start A
10	Shift reg. ground (both sides)
11	Video A
12	Screen and substrate
13	Screen and substrate
14	V ref (both sides)
15	Video B
16	Shift reg. ground (both sides)
17	Scan start B
18	N/C
19	Ø 1B
20	Ø 2B
21	N/C
22	Shift reg. ground (both sides)
23	End of scan B
24	End of scan ground

Package Details









Notes

1 Photodiode array centre line falls on the centre line of the package to a tolerance of ± 0.010"

2 Chip surface to package surface 0.051".

3 The refractive index of the package lid is 1.53

4 All the arrays scan towards Pin 1.

5 All dimensions are in inches.

Technical Specification

Performance measured at 20°C. Electro-optical parameters obtained with a tungsten filament source at 2870°K

Electrical Characteristics

Parameter	Value Min	Value Typ	Value Max	Unit
Min. shift register operating frequency	.	100	.	Hz
Max shift register operating frequency	.	5×10^6	.	Hz
Minimum clock width	.	200	.	ns
Clock amplitude	-23	-24	-25	V
Scan start pulse amplitude	-23	-24	-25	V
Clock crossover voltage	.	.	-2	V
Scan pulse overlap on trailing edge of Ø1	30	.	.	ns
V ref (1µA max current)	.	-8.5	.	V
Video line bias	.	-10	.	V
Clock line capacitance				
1024	.	170	.	pF
512	.	90	.	pF
256	.	50	.	pF
Video line capacitance				
1024	.	60	.	pF
512	.	31	.	pF
256	.	17	.	pF

Electro-Optical Characteristics

Parameter	Device Type M1	Device Type M5	Device Type M11	Unit
Responsivity	0.8	4.5	10	pA/µW/cm² (note 1)
Saturation exposure	21	3	1	µW sec/cm²
Saturation charge	17	14	10	pC
Uniformity of response	± 8	± 8	± 8	% of signal (note 1)
Dark fixed pattern noise	0.15	0.15	0.15	pC peak-peak (note 2)
Dark current equivalent	8	1.4	0.64	µW/cm² at 20°C (notes 1, 2)
Centre to centre spacing	1×10^{-3}	1×10^{-3}	1×10^{-3}	inches
Aperture width	1×10^{-3}	5×10^{-3}	11×10^{-3}	inches (see note 3)

Absolute Maximum Ratings

	Min	Max	
Voltage applied to any pin with respect to substrate	+ 0.2	-30	Volts
Ambient operating temperature	-10	+ 70	°C
Storage temperature	-20	+ 85	°C

Notes

1 Using a 2870K tungsten light source.

2 A + 2V bias applied to pins 2, 8 and 9 (256M and 512M) or pins 2, 12, and 13 (1024M) with respect to the shift register ground pin reduces these figures to approximately 60%.

3 The wide aperture array is specified by the suffix after the letter M. The 256 M5 is the 256 element array with the 0.005" aperture.

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DT1 1SY, U.K.
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APPENDIX 111

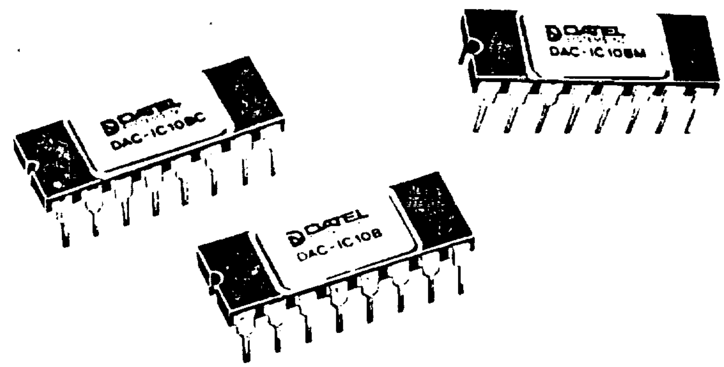
10 BIT D-A: INFORMATION SHEET AND CALCULATIONS

DATEL SYSTEMS, INC.

LOW COST, 10 BIT MONOLITHIC DIGITAL TO ANALOG CONVERTER

DAC-IC10B SERIES

FEATURES
- ▶ **10 Bit Resolution**
- ▶ **Straight Binary Coding**
- ▶ **Current Output**
- ▶ **250 nsec. Settling Time**
- ▶ **TTL/CMOS Compatible**
- ▶ **Low Cost**



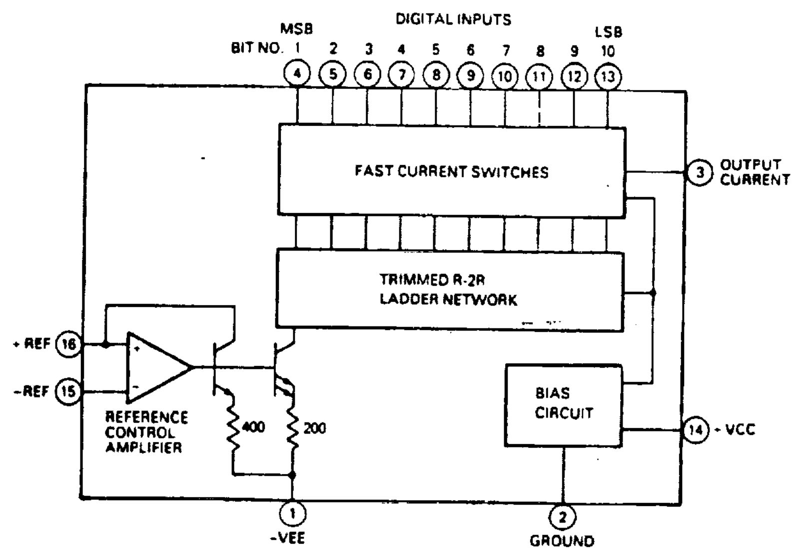
GENERAL DESCRIPTION

The DAC-IC10B is a low cost, 10 bit monolithic DAC with fast output current settling time. It is packaged in a 16 pin ceramic DIP and requires only an external reference and operational amplifier for voltage output operation. A full scale change in output current settles in 250 nanoseconds, and with a fast I.C. op amp (such as Datel Systems AM-452) a 10V output change can settle within 1 microsecond. Digital input coding is straight binary for unipolar operation, and offset binary for bipolar operation; the logic inputs are compatible with TTL or CMOS.

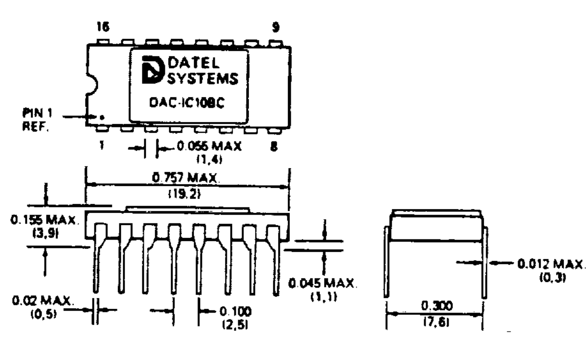
This converter is manufactured with monolithic bipolar technology. The circuit incorporates 10 fast switching current sources which drive a diffused resistor R-2R network. The ladder network is laser trimmed by cutting aluminum links. The circuit also contains a reference control amplifier and a bias circuit. An external reference current of 2 mA is required at the + Reference input terminal; this is accomplished by an external voltage reference and a metal film resistor.

Other characteristics of the DAC-IC10B include linearity to ±½ LSB and guaranteed monotonic performance. The gain temperature coefficient of this unit is typically −20ppm/°C. Output voltage compliance is −2.5V to +0.2V, permitting direct driving of a 625 ohm resistor for a voltage output. The reference input current can be varied from 0.5 mA to 2.5mA to give monotonic operation as a one or two quadrant multiplier.

Power supply requirement is +5VDC and −15VDC. The DAC-IC10B is available in three models covering two temperature ranges, 0°C to +70°C and −55°C to +125°C.



MECHANICAL DIMENSIONS INCHES (MM)



INPUT/OUTPUT CONNECTIONS

PIN	FUNCTION
1	$-V_{EE}$
2	GROUND
3	OUTPUT CURRENT
4	BIT 1 IN (MSB)
5	BIT 2 IN
6	BIT 3 IN
7	BIT 4 IN
8	BIT 5 IN
9	BIT 6 IN
10	BIT 7 IN
11	BIT 8 IN
12	BIT 9 IN
13	BIT 10 IN
14	$+V_{CC}$
15	−REFERENCE
16	+REFERENCE

SPECIFICATIONS DAC-IC10B
(Typical at 25°C, V_{CC} = +5V, V_{EE} = −15V, I_{REF} = 2.0 mA)

MAXIMUM RATINGS

V_{CC}	+7.0 Volts
V_{EE}	+18.0 Volts
Digital Input Voltage	+15 Volts
Output Voltage, Pin 3	+0.5, −5.0 Volts
Ref. Current	2.5 mA
Diff. Ref. Voltage	0.7V

INPUTS

Resolution	10 Bits
Coding, Unipolar Output	Straight Binary
Coding, Bipolar Output	Offset Binary
Input Level, Logic "1"	+2.0 to +15V @ +40μA
Input Level, Logic "0"	0 to +0.8V @ −0.4 mA
Nom. Ref. Current, Pin 16	2.0 mA
Reference Current Range	0.5 mA to 2.5 mA
Ref. Bias Current, Pin 15	−5 μA max.

OUTPUTS

Output Current	4.0 mA ±0.2 mA
Output Current Range	0 to 5.0 mA
Output Current, All Bits "0"	2.0 μA max.[1]
Output Voltage Compliance	−2.5 to +0.2V
Output Capacitance	25 pF

PERFORMANCE

Linearity Error, B, BM	±½ LSB, max.
BC	±1 LSB, max.
Diff. Linearity Error	±½ LSB
Monotonicity, B, BM	Full Temp. Range[2]
BC	At 25°C
Gain Tempco	−20 ppm/°C, 60 ppm/°C max.[3]
Ref. Current, Slew Rate	20 mA/μsec.
Ref. Current Settling	2.0 μsec.[4]
Output Current Settling	250 nsec.[5]
Update Rate	4 MHz
Power Supply Sensitivity	.02%/% max.

POWER REQUIREMENT

V_{CC} Voltage	+5 VDC ±0.25V
V_{CC} Current	18 mA max.
V_{EE} Voltage	−15 VDC ±0.75V
V_{EE} Current	−20 mA max.

PHYSICAL ENVIRONMENTAL

Operating Temp. Range	
DAC-IC10B, BC	0°C to +70°C
DAC-IC10BM	−55°C to +125°C
Storage Temp. Range	−65°C to +125°C
Package	16 Pin Ceramic DIP

NOTES:
1. 4.0 μA max. for DAC-IC10BC only.
2. All converters in this series typically retain rated monotonicity for values of input reference current from 0.5 mA to 2.5 mA.
3. 70 ppm/°C max. for DAC-IC10BM only.
4. Zero to 4 mA output change to 0.1%.
5. Full scale change to ½ LSB.

ORDERING INFORMATION

MODEL	OPER. TEMP RANGE
DAC-IC10BC	0°C to +70°C
DAC-IC10B	0°C to +70°C
DAC-IC10BM	−55°C to +125°C

THESE CONVERTERS ARE COVERED BY GSA CONTRACT.

TECHNICAL NOTES

1. The *General Connection Diagram* shows the basic connections for the converter. The scale factor is set by a reference current injected into pin 16. Pins 15 and 16 are the input terminals to the reference control amplifier. When connected as shown, pin 15 is grounded through R_{15} and pin 16 is at virtual ground. Therefore, the reference current is determined by the external voltage reference and R_{16}: $I_{REF} = V_{REF}/R_{16}$. R_{16} should be a stable metal film resistor. R_{15} is used only to compensate for the input bias current into pin 15 (1 μA typical). R_{15}, if used, should be equal to R_{16} and may be a carbon composition type. An I_{REF} of 2.0 mA is recommended for most applications.

2. There is a second method of connecting the reference shown in *Two Ways to Connect Reference.* A negative reference can be applied to pin 15. In this case only the bias current must be supplied from the reference since pin 15 is a high impedance input. Pin 16 is at the negative voltage and I_{REF} still flows into pin 16. Again, R_{15} is used only to compensate for bias current. There is an important requirement for this connection: **the negative reference voltage must always be 3 volts above V_{EE}.**

3. I_{OUT} is inversely proportional to the reference input current (I_{REF}) times the digital word. Scaling of the applied reference can be represented as follows:

$$I_{OUT} = -2\left(\frac{V_{REF}}{R_{REF}}\right)\left(\frac{A_n}{2^n}\right)$$

where n = 10 (10 bit DAC)
A_n = digital code

Note: 1) The largest digital code for a 10 bit DAC is 1023.
2) The reference current is scaled by a factor of 2 within the DAC.

Example:

$$I_{OUT}(FS) = -2\left(\frac{2.5V}{1.25K}\right)\left(\frac{1023}{1024}\right)$$
$$= -3.996 \text{ mA (nominal)}$$

$$I_{OUT}(ZERO) = -2\left(\frac{2.5V}{1.25K}\right)\left(\frac{0}{1024}\right)$$
$$= 0 \text{ mA (nominal)}$$

4. The reference amplifier is internally compensated. The minimum reference current supplied from a current source is 0.5 mA for stability.

5. The voltage on pin 3 is restricted to a range of −2.5V to +0.2V. This compliance voltage is guaranteed at 25°C and nearly constant over temperature.

6. Full scale output current of 3.996 mA is guaranteed for input reference currents to pin 16 between 1.9 and 2.1 mA.

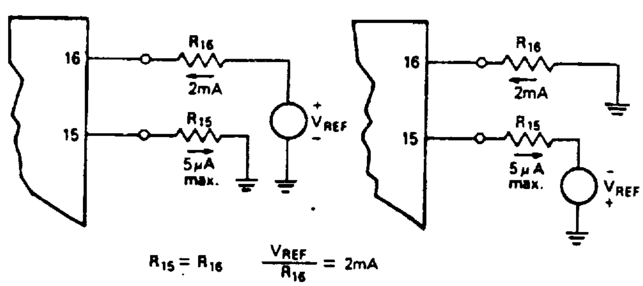
7. It is recommended that pin 14 (V_{CC}) and pin 1 (V_{EE}) always be bypassed to ground with at least 0.1 μF capacitors located close to the pins.

8. The accuracy of the converter is specified for a reference current of 2.0 mA; the accuracy, however, is essentially constant for reference currents from 1.5 mA to 2.5 mA. Typically, this device is monotonic for all values of reference current above 0.5 mA.

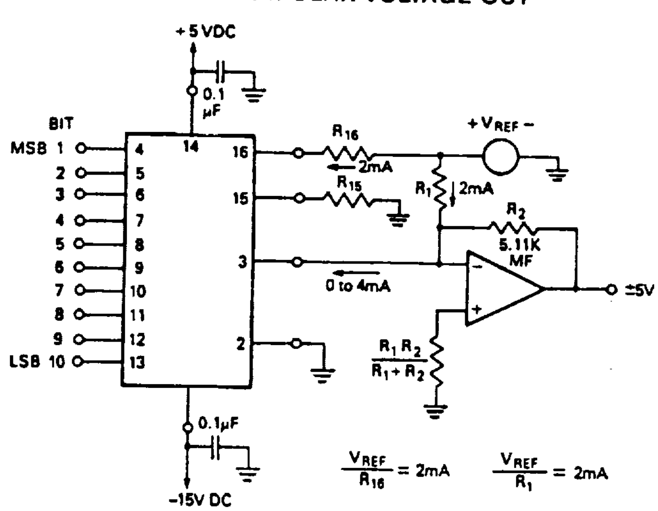
TECHNICAL NOTES (cont'd.)

9. For fastest voltage output settling times in either unipolar or bipolar modes, two circuits using Datel Systems AM-452 monolithic operational amplifiers are recommended. These circuits, with the compensation shown, result in output settling times of typically 550 nsec. for a 10 volt change to 1 LSB. This is the worst case settling time which occurs when all bits are turned on. For current output and R_L less than 500 ohms, this time is 250 nsec.; when all bits are turned off the time is shorter, typically 100 nsec. The two circuits shown also illustrate a simple method of deriving both reference current and offset current from a precision 6.4 volt Zener reference diode.
10. Both one and two quadrant multiplication are also possible with the converter as shown in the two diagrams. V_{IN} is shown operating into pin 16; this results in an input impedance of 2.5K. Alternatively, V_{IN} can be applied to pin 15 for a high impedance input as explained previously. The range of V_{IN} is then 0 to −10V. For two quadrant multiplication V_{IN} is unipolar and the digital input is bipolar with offset binary coding. V_{OUT} then varies over the bipolar range of ±5 volts. In multiplication applications, it is recommended that full scale I_{REF} be set to 2.0 mA; the output is then monotonic as the reference current varies over 0.5 mA to 2.0 mA.

TWO WAYS TO CONNECT REFERENCE

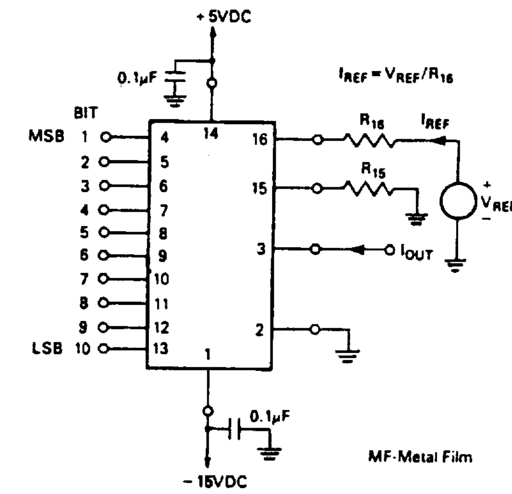


CONNECTION FOR BIPOLAR VOLTAGE OUT

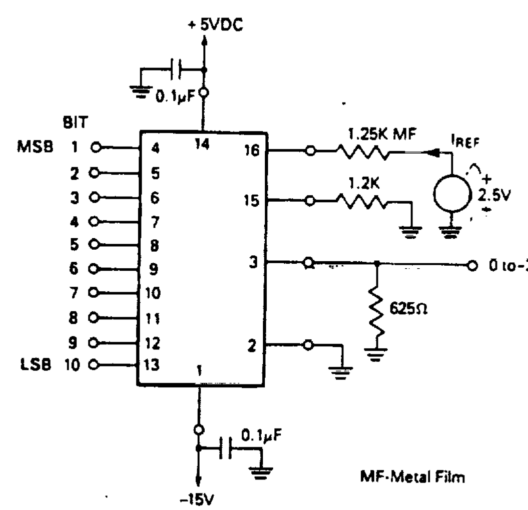


CONNECTION DIAGRAMS

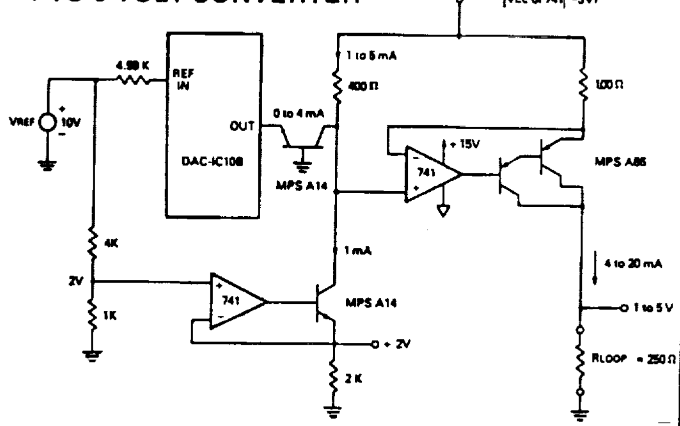
GENERAL CONNECTION DIAGRAM



CONNECTION FOR DIRECT VOLTAGE OUTPUT

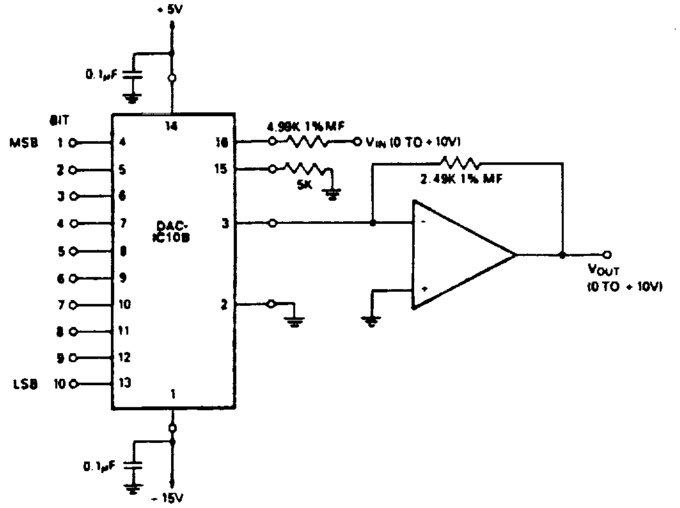


DIGITAL 4 TO 20 MA OR 1 TO 5 VOLT CONVERTER

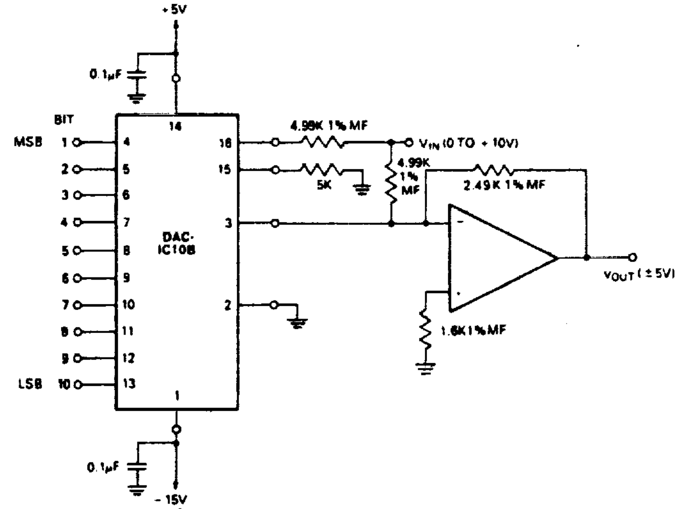


APPLICATION DIAGRAMS

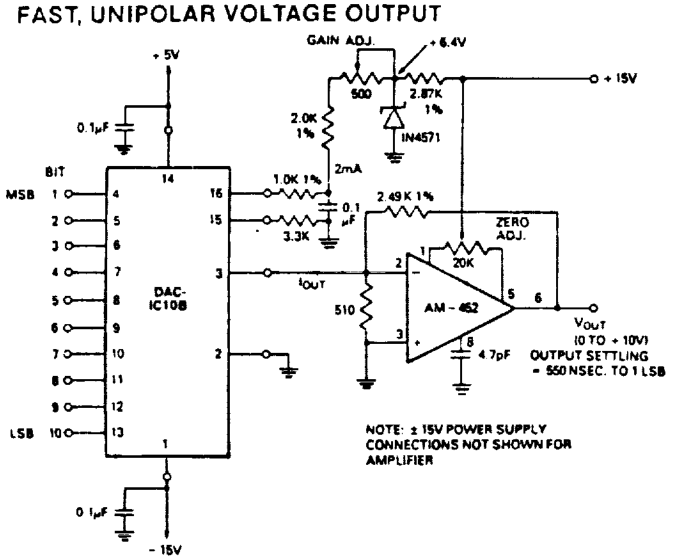
ONE QUADRANT MULTIPLICATION



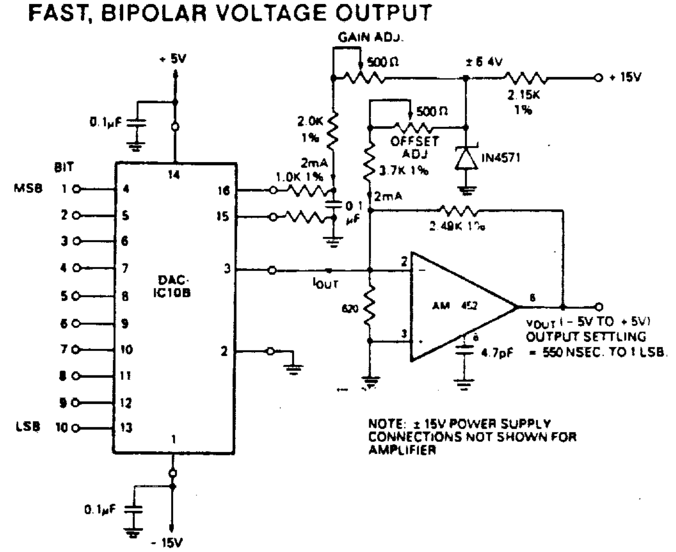
TWO QUADRANT MULTIPLICATION



FAST, UNIPOLAR VOLTAGE OUTPUT



FAST, BIPOLAR VOLTAGE OUTPUT



CALIBRATION AND CODING TABLE

1. Select the desired output range by means of the feedback resistor of the external operational amplifier and the externally programmed reference current.
2. *Zero and Offset Adjustments*/ For unipolar operation, set all digital inputs to "0" (0V to +0.8V) and adjust the output amplifier ZERO ADJUSTMENT for zero output voltage. For bipolar operation, set all digital inputs to "0" (0 to +0.8V) and adjust the OFFSET ADJUSTMENT for the negative full scale voltage shown in the Coding Table.
3. *Gain Adjustment*/ For either unipolar or bipolar operation, set all digital inputs to "1" (+2.0 to +5.5V) and adjust the GAIN ADJUSTMENT for the positive full scale voltage shown in the Coding Table.

INPUT CODE	UNIPOLAR OPERATION—STRAIGHT BINARY			
MSB LSB	0 TO +5V	0 TO +10V	0 TO −2MA	0 TO −4MA
11 1111 1111	+4.995V	+9.990	−1.998 MA	−3.996
11 1000 0000	+4.375	+8.750	−1.750	−3.500
11 0000 0000	+3.750	+7.500	−1.500	−3.000
10 0000 0000	+2.500	+5.000	−1.000	−2.000
01 0000 0000	+1.250	+2.500	−0.500	−0.100
00 0000 0001	+0.005	+0.010	−0.002	−0.004
00 0000 0000	0.000	0.000	0.000	0.000

INPUT CODE	BIPOLAR OPERATION—OFFSET BINARY CODING			
MSB LSB	±5V	±10V	±1MA	±2MA
11 1111 1111	+4.990V	+ 9.980V	−0.998MA	−1.996MA
11 1000 0000	+3.750	+ 7.500	−0.750	−1.500
11 0000 0000	+2.500	+ 5.000	−0.500	−1.000
10 0000 0000	0.000	0.000	0.000	0.000
01 0000 0000	−2.500	− 5.000	+0.500	+1.000
00 0000 0001	−4.990	− 9.980	+0.998	+1.996
00 0000 0000	−5.000	−10.000	+1.000	+2.000

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APPENDIX 111 (cont.)

CALCULATIONS FOR 10 BIT D-A

The circuit diagram used for the 10 bit D-A is shown in figure 14 in the report and reference will need to be made to this and the data sheet.

The output voltage swing as the counter goes from zero to 511 must be calculated at pin 3. In order to do this, the reference voltage between the two 100Ω resistors at pin 16 must be estimated. Regarding pin 16 as a virtual earth, one obtains 2.4 volts for this figure with a 5 volt supply and a 1.2KΩ series resistor:

Then I_{out} (full scale)

$$= -2\left(\frac{2.4}{1.2}\right)\left(\frac{511}{1024}\right) = -2mA$$

This flows through a 680Ω resistor at pin 3 so voltage swing is:

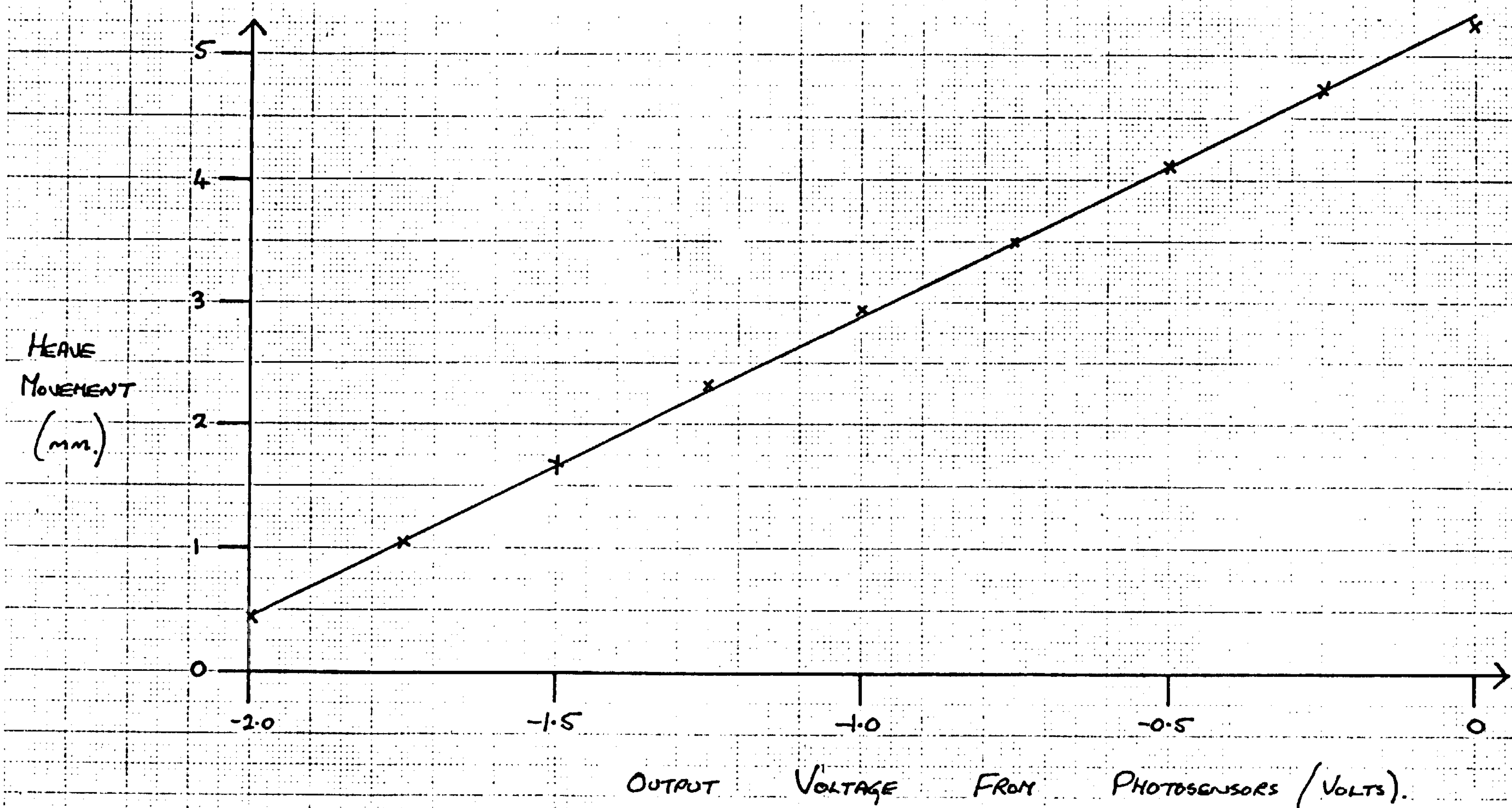
-1.36v at 511

to 0v at 0

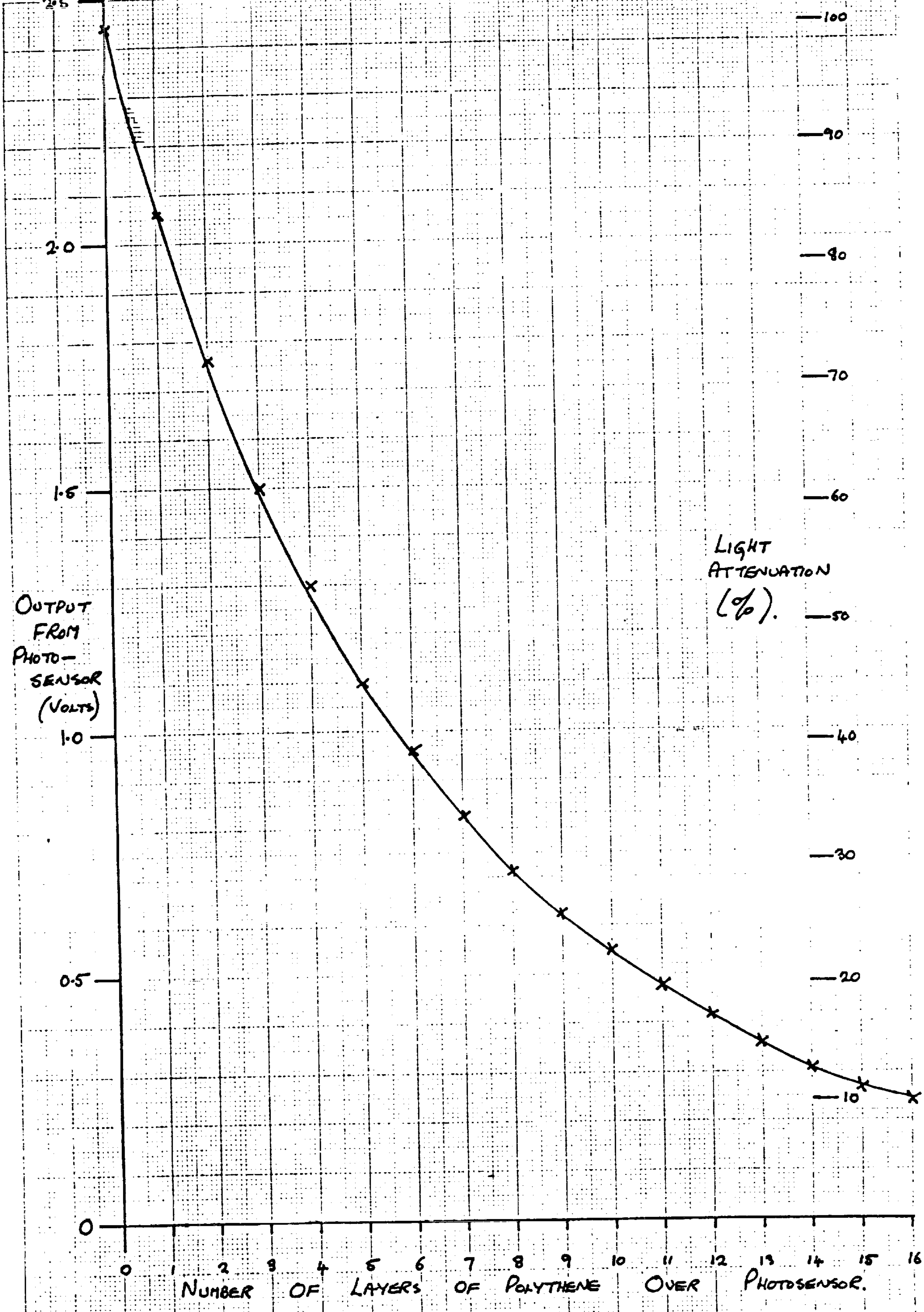
The op-amp resistors used on the output then give, with an input of -1.36 volts, an output range of 2.8 volts to 6.9 volts.

APPENDIX 1V

GRAPHS: PHOTOSENSOR CALIBRATION AND LIGHT ATTENUATION BY POLYTHENE



GRAPH 3. Photosensor Calibration Curve.



GRAPH 4. Light Attenuation of Polythene.

APPENDIX V

COSTING

Apart from the I.P.L. board and the optics system, the remaining components cost the following:

		£ -
1x	4011	0=23
5x	4013	2=80
1x	4040	1=02
2x	4071	0=50
1x	TL081	0=24
1x	741	0=23
10x	BC182L	0=70
10x	LEDs	1=10
22x	Resistors	0=22
2x	Capacitors	0=18
10 bit D-A:		
	DATEL IC10B	7=82
Associated components		0=77
	TOTAL	£15=81
8 bit D-A:		
	DAC 0800	2=04
Associated components		1=07

ACKNOWLEDGEMENTS

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